11/16/05 ... Book titles ordered

Web Images Groups News Froogle Local New! more »

Google Print BETA

teds and software and transducer | Search | Advanced Print Search

The "AND" operator is unnecessary -- we include all search terms by default. [details]

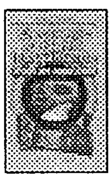
Print

Books **1** - **5** with **11** pages on **teds and software and transducer**. (**0.06** seconds)

Did you mean: ***ted's and software and transducer***

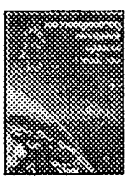
Feb.

Modern Component Families and Circuit Block Design
by Nihal Kularatna - Technology - 2000 - 384 pages
Page 332 - Dynamic configuration of measurement and control loops via **software**. ...
Communication and **Transducer** Electronic Data Sheet (**TEDS**) formats for distributed ...
[More results from this book]



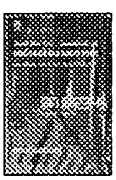
Electronic Portable Instruments
by Halit Eren - Technology - 2003 - 335 pages
Page 220 - The second section, 1451.2, concerns transducers and is titled "Microprocessor
Communication Protocols and **Transducer** Electronic Data Sheet (**TEDS**). ...
[More results from this book]

Jan.



Microengineering Aerospace Systems
edited by Henry Helvajian - Technology - 1999 - 707 pages
Page 398 - Each **transducer** will be physically associated with **TEDS**. Two draft standards for the Smart **Transducer** Interfacet have been proposed, the Network Capable ...
[More results from this book]

Practical Tcp/Ip and Ethernet Networking
by Deon Reynders, Edwin Wright - Computers - 2003 - 320 pages
Page 241 - [Sorry, this page's content is restricted]
[More results from this book]



Digital and Analogue Instrumentation
by Nihal Kularatna - Technology - 2002 - 630 pages
Page 588 - [Sorry, this page's content is restricted]
[More results from this book]

teds and software and transducer | Search all books | Search the Web

Modern Component Families and Circuit Block Design

by Nihal Kularatna - Provided by Newnes through the Google Print Publisher Program

Synopsis

Kularatna's new book describes modern component families and how to design circuit blocks using them. While much of this information may be available elsewhere, in Modern Component Families and Circuit Block Design it is integrated with additional design hints that are unique. The discussion covers most components necessary in an embedded design or a DSP-based real time system design. The chapter on modern semi-conductor sensors allows system designers to use the latest sensor ICs for real-world physical parameter sensing.
*Covers the most recent low-power components
*Written by an authority on power electronics
*Includes extensive illustrations and references

Reviews

. . .this book can serve as a valuable resource and application idea source for upper-division undergraduate students and faculty involved in electronic design activities; professional desig engineers; and two-year technical program students.
E.M. Aupperle, University of Michigan
...beneficial not only to reinforce their technical foundation, but also to update themselves witl the ever-altering electronic component systems technology
- IEEE Circuits and Devices Magazine, Sept./Oct. 2004

Related information

- Web search for reviews of **Modern Component Families and Circuit Block Design**
- Other web pages related to **Modern Component Families and Circuit Block Design**

Bibliographic information

Title	Modern Component Families and Circuit Block Design
Author(s)	Nihal Kularatna
Publisher	Newnes
Publication Date	Feb 17, 2000
Subject	Technology & Industrial Arts
Format	Paperback
Pages	384

Dimensions	5.99 x 9.12 x 0.92 in
ISBN	0750699922

teds and software and transducer | Search all books | Search the Web

Google Print Help | Provide Feedback | Advanced Print Search

About Google Print - Information for Publishers - Google Home

phdabney@yahoo.com | My Account | Sign out

Google Print BETA

teds and software and transducer | Search this book | Search all books

Microengineering Aerospace Systems

edited by Henry Helvajian - Provided by AIAA through the Google Print Publisher Program

« Back to Search results

Front Cover

Copyright

Table of Contents

Index

Back Cover

More results from this book

About this Book

AIAA

Buy this Book

Amazon.com

Barnes&Noble.com

BookSense.com

Froogle

About Google Print

Synopsis

Microengineering Aerospace Systems is a textbook tutorial encompassing MEMS (micro-electromechanical systems), nanoelectronics, packaging, processing, and materials characterization for developing miniaturized smart instruments for aerospace systems (i.e., ASIM application-specific integrated microinstrument), satellites, and satellite subsystems. Third in a series of Aerospace Press publications covering this rapidly advancing technology, this work presents fundamental aspects of the technology and specific aerospace systems applications through worked examples.

Related information

- Web search for reviews of **Microengineering Aerospace Systems**
- Other web pages related to **Microengineering Aerospace Systems**

Bibliographic information

Title	Microengineering Aerospace Systems
Editor(s)	Henry Helvajian
Publisher	AIAA
Publication Date	Jan 1, 1999
Subject	Technology & Industrial Arts
Format	Hardcover
Pages	707
ISBN	1884989039

teds and software and transducer | Search all books | Search the Web

Google Print Help | Provide Feedback | Advanced Print Search

About Google Print - Information for Publishers - Google Home

09/610284

564346 138

Johnson, Kimberly (STIC)

From: Dabney, Phylesha L.
Sent: Wednesday, November 16, 2005 8:11 PM
To: STIC-EIC2600
Subject: ILL Order

Requester:
Phylesha Dabney (TC2600)
Art Unit:
2646
Office Location:
knx 6 d 68
Phone_Number:
571-272-7494
Application Number:
09/610284

Google Books List

Item Information

Author:
Nihal Kularatna

Article or Chapter Title:
Sensors

Journal or Book Title:
Modern Component Families and Circuit Block Design

Volume and issue:

Year of Publication:
2000

Page numbers:
332-384

Other Identifying Information (Edition, ISSN, ISBN, etc.):

11/17/05
KeJ
NOS
ILL

MITS ordered

Control networks provide many benefits for transducers:

- Significant reduction in installation costs by eliminating many and long analog wires.
- Acceleration of control loop design cycles, reduction of commissioning time, and reduction of downtime.
- Dynamic configuration of measurement and control loops via software.
- Addition of intelligence by leveraging the microprocessors used for digital communication.

For anyone attempting to choose a sensor-interface or networking standard, the range of choices is overwhelming. Some standards are open, and some are proprietary to a company's control products. To remedy the situation, the IEEE Sensor Technology Committee TC-9 is developing the IEEE P1451, Standard for Smart Transducer Interface for Sensors and Actuators. The sensor market comprises widely disparate sensor types. Designers consume relatively large amounts of all types of sensors. However, the lack of a universal interface standard impedes the incorporation of "smart" features, such as an onboard electronic data sheet, onboard A/D conversion, signal conditioning, device-type identification, and communications hand-shaking circuitry, into the sensors. In response to the industry's need for a communication interface for sensors, the IEEE with cooperation from the National Institute of Standards and Technology (NIST), decided to develop a hardware-independent communication standard for low-cost smart sensors that includes smart transducer object models for control networks (Travis, 1995).

The IEEE P1451 standards effort, currently under development, will provide many benefits to the industry. P1451, "Draft Standard for Smart Transducer Interface for Sensors and Actuators," consists of four parts, namely:

(i) IEEE 1451.1—Network Capable Application Processor (NCAP) information model,
(ii) IEEE 1451.2—Transducer to Microprocessor Communications Protocols and Transducer Electronic Data Sheet (TEDS) formats,
(iii) IEEE P1451.3—Digital Communication and Transducer Electronic Data Sheet (TEDS) formats for distributed multidrop systems, and
(iv) IEEE 1451.4—Mixed-mode Communication Protocols and Transducer Electronic Data Sheet (TEDS) formats.

In the process of writing the draft document, the working group has defined the smart transducer interface module (STIM), transducer electronic data sheet (TEDS), transducer-independent interface (TII), and a set of communication protocols between the STIM and the network capable application processor (NCAP).

A system block diagram depicting the interface is shown in Figure 7-46. A STIM is specified to include up to 255 transducers, a signal converter or conditioning, a TEDS, and the necessary logic circuitry to support digital communication

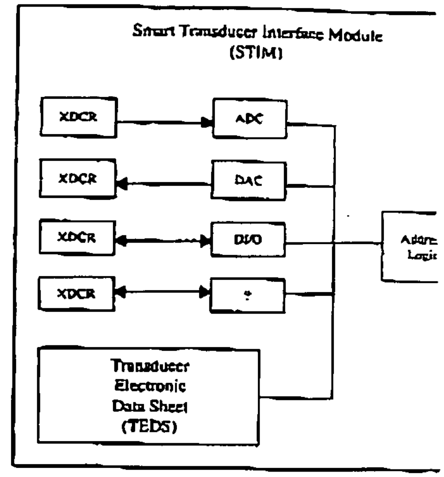


FIGURE 7-46 System block diagram de[…] NIST)

with NCAP. The TEDS is a small physi[…] information and data for the transducer i[…] 10-wire digital interface with provision f[…] is used to access the TEDS, read sensors[…]

Figure 7-47(a) depicts a STIM and[…] scribed in the P1451.2-1997 hot swap. Th[…] of a network-node microprocessor. In ad[…] STIMs can be used with microprocessor[…] portable instruments and data acquisitio[…]

TABLE 7-5 The ten lines that make […] (Courtesy of NIST)

Line	*Driven by*	*Function*
DIN	NCAP	Address and […]
DOUT	STIM	Data transpo[…]
DCLK	NCAP	Positive-goin[…] DOUT
NIOE	NCAP	Signals that […] transport
NTRIG	NCAP	Performs trig[…]
NACK	STIM	Serves two f[…] transport
NINT	STIM	Used by the […]
NSDET	STIM	Grounded in […] the prese[…]
POWER	NCAP	Nominal 5 V[…]
COMMON	NCAP	Signal comm[…]

ɔnefits for transducers:

osts by eliminating many and long analog

cycles, reduction of commissioning time,

ent and control loops via software.
ing the microprocessors used for digital

. sensor-interface or networking standard, Some standards are open, and some are ducts. To remedy the situation, the IEEE s developing the IEEE P1451, Standard nsors and Actuators. The sensor market ɔes. Designers consume relatively large 'er, the lack of a universal interface stan- :t" features, such as an onboard electronic gnal conditioning, device-type identifica- ʒ circuitry, into the sensors. In response .tion interface for sensors, the IEEE with ɜ of Standards and Technology (NIST), lent communication standard for low-cost lucer object models for control networks

:urrently under development, will provide "Draft Standard for Smart Transducer ɔnsists of four parts, namely:

Application Processor (NCAP) informa-

croprocessor Communications Protocols ıeet (TEDS) formats,
ication and Transducer Electronic Data :ed multidrop systems, and
nmunication Protocols and Transducer nats.

locument, the working group has defined (STIM), transducer electronic data sheet ıce (TII), and a set of communication network capable application processor

the interface is shown in Figure 7-46. A transducers, a signal converter or condi- :ircuitry to support digital communication

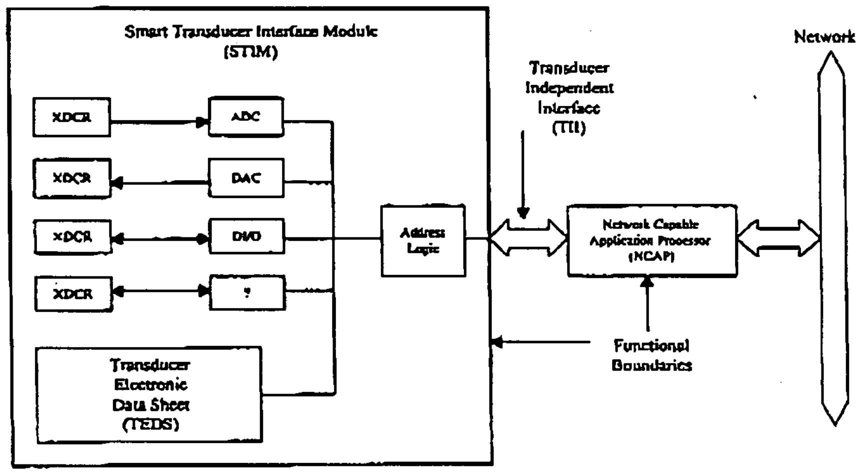


FIGURE 7-46 System block diagram depicting the transducer interface (Courtesy of NIST)

with NCAP. The TEDS is a small physical memory containing manufacturer's information and data for the transducer in a standardized data format. The TII, a 10-wire digital interface with provision for hot-swapping a sensor to a network, is used to access the TEDS, read sensors, and set actuators.

Figure 7-47(a) depicts a STIM and the associated digital interface as described in the P1451.2-1997 hot swap. The STIM shown here is under the control of a network-node microprocessor. In addition to their use in control networks, STIMs can be used with microprocessors in a variety of applications, such as portable instruments and data acquisition cards, as shown in Figure 7-47(b).

TABLE 7-5 The ten lines that make up the transducer-independent interface (Courtesy of NIST)

Line	*Driven by*	*Function*
DIN	NCAP	Address and data transport from NCAP to STIM
DOUT	STIM	Data transport from STIM to NCAP
DCLK	NCAP	Positive-going edge latches data on both DIN and DOUT
NIOE	NCAP	Signals that the data transport is active and delimits data transport framing
NTRIG	NCAP	Performs triggering function
NACK	STIM	Serves two functions: trigger acknowledge and data transport acknowledge
NINT	STIM	Used by the STIM to request service from the NCAP
NSDET	STIM	Grounded in the STIM and used by the NCAP to detect the presence of a STIM
POWER	NCAP	Nominal 5 V power supply
COMMON	NCAP	Signal common or ground

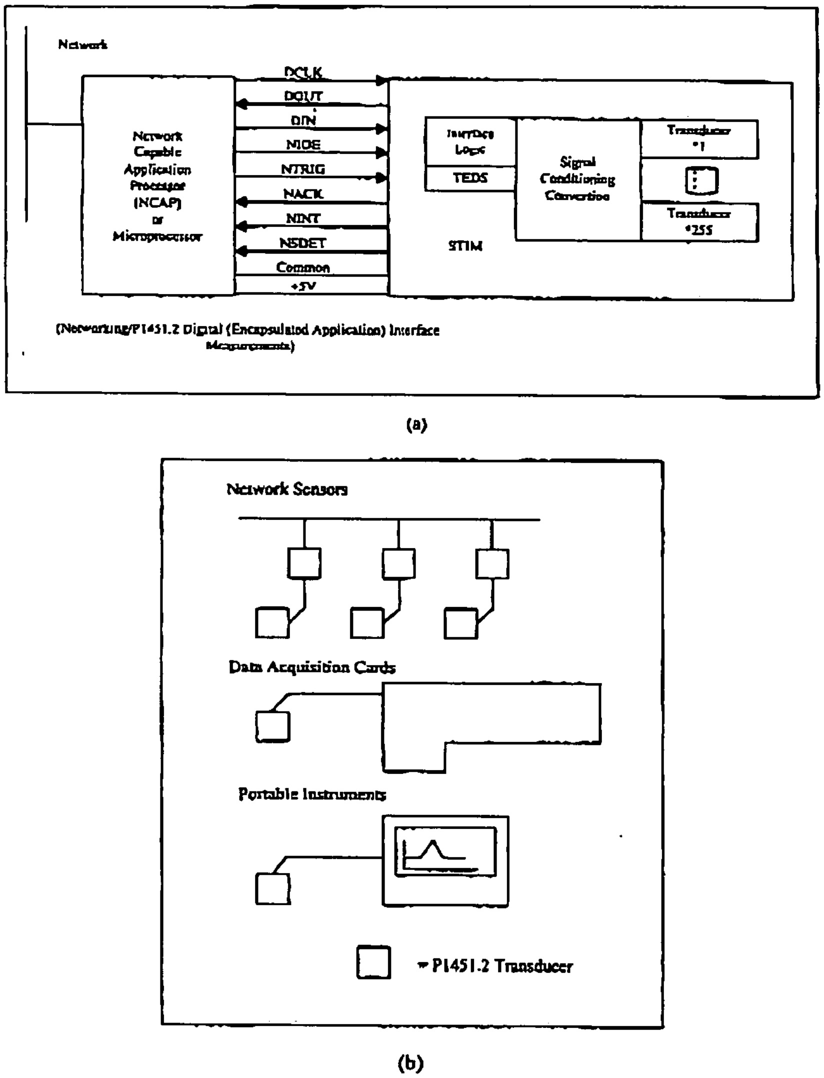


FIGURE 7-47 (a) Hardware partition proposed by P1451.2 and (b) possible use for the interface. (Source: Woods, 1996.)

The origin and function of each signal line of the ten-wire interface is listed in Table 7-5.

1451.2 was adopted by the IEEE as a full use standard, designated as IEEE Std. 1451.2-1997. The IEEE Std. 1451.2-1997 can be applied standalone, or it can be used with P1451.1. The two documents together will define a standard interface

for networked smart sensors and actuato
be implemented in a sensor control or f

The IEEE Std. 1451.2-1997 standa
ordered from the IEEE customer service
(IEEE) in the United States and Cana
United States and Canada, or by faxing

7.10 P1451 and Practical Cc

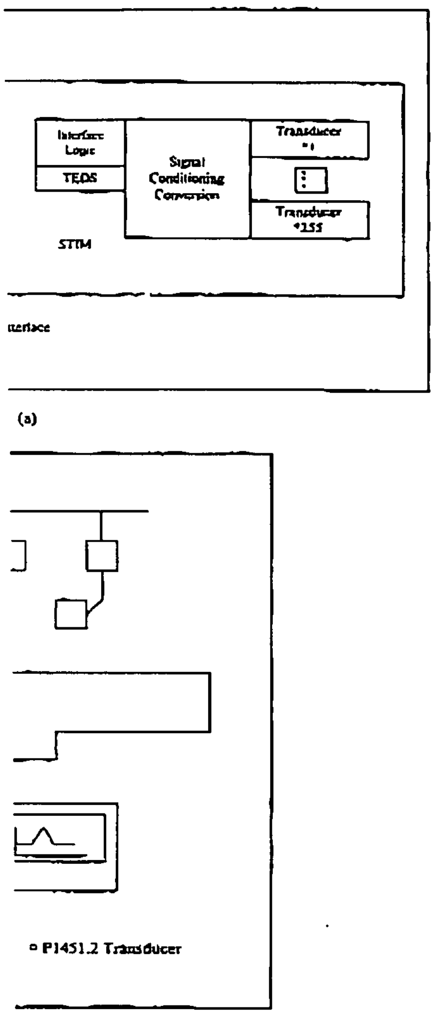
Existing microcontrollers fall shor
silicon, either because of functionality
standard transducer interface module (S
the sensor interface electronics, signal cc
linearization, basic communication capab
Some microcontrollers with integrated &
slope conversion can implement most of
in conversion speed and accuracy. Mo
economically integrated analog conversi
because of the additional process comple

These limitations are overcome by 1
the AduC812 MicroConverter™ (Leona
integrates key STIM elements with 12-bi
for high-accuracy, fast-conversion-time a
pressure and temperature management, g
typical application, the AduC812 conditi
types of sensors, sends signals to actuat
cations with the host microprocessor ove

The AduC812 MicroConverter™ i
that includes documentation, applications
and software. Provided on a 3.5-inch fl
assembler, simulator, debugger, serial do

References

Ajluni, C. "Pressure Sensors Strive to Stay on Top."
Analog Devices, Inc. *Design*. In *Reference Manual*.
Analog Devices, Inc. "Data Sheet: Serial Outpu
Devices, Inc., MA, USA 1995a.
Analog Devices, Inc. "Data Sheet: Airflow and T
Devices, Inc., MA, USA 1995b.
Analog Devices, Inc. "Data Sheet: Low Voltage Ten
rev. 0, MA, USA 1996a.
Analog Devices, Inc. "Data Sheet: ADXL 50," rev.
Analog Devices, Inc. "Accuracies of AD 590." A
Applications Reference Manual 1993, pp. 19-3 to
Analog Devices, Inc. "Practical Design Techniques f
Inc., USA 1999.



roposed by P1451.2 and (b) possible use for

l line of the ten-wire interface is listed

s a full use standard, designated as IEEE
-1997 can be applied standalone, or it can
ts together will define a standard interface

for networked smart sensors and actuators. Likewise, the P1451.1 information can be implemented in a sensor control or field network without 1451.2.

The IEEE Std. 1451.2-1997 standard and IEEE P1451.1 D2.2 draft can be ordered from the IEEE customer service department by calling 1-(800)-678-4333 (IEEE) in the United States and Canada, 1-(732)-981-0600 from outside the United States and Canada, or by faxing 1-(732)-981-9667.

7.10 P1451 and Practical Components

Existing microcontrollers fall short of fully implementing the standard in silicon, either because of functionality or prohibitive cost. For example, the standard transducer interface module (STIM) portion of the standard specifies the sensor interface electronics, signal conditioning, data conversion, calibration, linearization, basic communication capability, and a non-volatile 565-byte TEDS. Some microcontrollers with integrated 8- or 10-bit ADCs or comparator-based slope conversion can implement most of the STIM functionality, but are limited in conversion speed and accuracy. Moreover, few available controllers have economically integrated analog conversion together with high-density EEPROM because of the additional process complexity requirements of both functions.

These limitations are overcome by recently introduced components such as the AduC812 MicroConverter™ (Leonard, 1998) from Analog Devices, which integrates key STIM elements with 12-bit, 5 μs data conversion on a single chip for high-accuracy, fast-conversion-time applications such as battery monitoring, pressure and temperature management, gas monitoring, and leak detection. In a typical application, the AduC812 conditions and converts signals from various types of sensors, sends signals to actuators and display devices, and communications with the host microprocessor over signal and control lines.

The AduC812 MicroConverter™ is supported by a development system that includes documentation, applications board, power supply, serial port cable, and software. Provided on a 3.5-inch floppy disk, the software consists of an assembler, simulator, debugger, serial downloader, and example code.

References

Ajluni, C. "Pressure Sensors Strive to Stay on Top," *Electronic Design* (October 3, 1994), pp. 67–74.
Analog Devices, Inc. *Design*. In *Reference Manual*. Analog Devices Inc., USA, 1994.
Analog Devices, Inc. "Data Sheet: Serial Output Thermometers—TMP03/04," rev. 0, Analog Devices, Inc., MA, USA 1995a.
Analog Devices, Inc. "Data Sheet: Airflow and Temperature Sensor—TMP 12," rev. 0. Analog Devices, Inc., MA, USA 1995b.
Analog Devices, Inc. "Data Sheet: Low Voltage Temperature Sensors—TMP 35/TMP 36/TMP 37," rev. 0, MA, USA 1996a.
Analog Devices, Inc. "Data Sheet: ADXL 50," rev. B. Analog Devices, Inc., MA, USA 1996b.
Analog Devices, Inc. "Accuracies of AD 590." Application note AN-272. Analog Devices, Inc., Applications Reference Manual 1993, pp. 19-3 to 19-6.
Analog Devices, Inc. "Practical Design Techniques for Sensor Signal Conditioning," Analog Devices Inc., USA 1999.

Analog Devices, Inc. "Accelerometer Application Guide" (G 2112A). Analog Devices, Inc.

Bry Zek, J. "Characterization of MEMS Industry in Silicon Valley and Its Impact on Sensor Technology." Proceedings of Sensors Expo, October 1996, pp. 1–13.

Burri, M. "Calibration Free Pressure Sensor System." Application note AN-1097, Motorola Inc., Sensor Device Data, DL200/D, Rev. 2, 1995, pp. 4-19 to 4-23.

Caristi, A. J. "A Digital Pressure Gauge Using the Motorola MPX700 Series Differential Pressure Sensors." Application note AN-1105. Motorola Inc., Sensor Device Data, DL200/D, Rev. 2, pp. 4-27 to 4-31, 1995.

Dallas Semiconductor. *System Extension Data Book.* Dallas Semiconductor, TX, 1994–1995.

Demington, C. "Compensating for Non-Linearity in the MPX10 Series Pressure Transducer." Application note AN 935, Motorola Inc., Sensor Device Data, DL200/D, Rev. 2, 1995, pp. 4-4 to 4-10.

FiS Inc. *SB Products Review: Sensors and Systems Technology.* Japan: FiS Inc., 1996.

Freeman, W. "Solid State Temperature Sensors Protect and Control." PCIM (November 1993), pp. 39–45.

Guckel, H. "Micromechanisms Fabrication: Challenge in Micromechanisms and Microelectricity." ISSCC Proceedings, 1992 (IEEE Catalog Number 92CH3128-6), pp. 14–17.

Hauptmann, P. *Sensors—Principals and Applications.* Englewood Cliffs, NJ: Prentice-Hall, 1991.

IC Sensors. "Temperature Compensation—IC Pressure Sensors." Application note TN-002, IC Sensors, March 1985.

IC Sensors. "Signal Conditioning for IC Pressure Sensors." Application note TN-001. IC Sensors, April 1988.

IC Sensors. "Model 3255 Accelerometer." Application note TN-010. IC Sensors, April 1995.

IC Sensors. "Understanding Accelerometer Technology." Application note UATRO-9111. IC Sensors, Milpitas, CA, USA.

Jacobson, E. "Designing Amplifiers for Sensor Applications: A Cookbook Approach." *EDN* (January 4, 1996), pp. 119–128.

Jacobson, E., and J. Baum. "Optimize Sensor Systems Using Fixed Components." *EDN* (July 6, 1995), pp. 85–95.

Jacobson, E., and J. Baum. "The A-B-C's of Signal Conditioning Amplifier Design for Sensor Applications." Application note AN 1525. Motorola Inc., Sensor Device Data, DL200/D, Rev. 2, pp. 4-152 to 4-158, 1995.

Klonowski, P. "Use of the AD 590 Temperature Transducer in a Remote Sensing Application." Application note AN-273. Analog Devices, Inc., MA, USA.

Leonard, M. "Self-Programming Microcontroller Networks Sensors & Transducers." *Electronic Design* (February 9, 1998), pp. 92–94.

Le Fort, B., and B. Ries. "Taking the Uncertainty out of Thermocouple Temperature Measurement (with AD594/AD595)." Application note AN-274, Analog Devices, Inc., Norwood, MA, USA.

Lucus, B. "An Evaluation System for Direct Interface of MPX5100 Pressure Sensor with a Microprocessor." Application note AN 1305. Motorola Inc., Sensor Device Data, DL200/D, Rev. 2, pp. 4-42 to 4-57, 1995.

Marcin, J. "Thermocouple Signal Conditioning Using the AD594/AD595." Application note AN-369. Analog Devices, Inc., Norwood, MA, USA.

Microswitch. "Pressure, Force and Airflow Sensors." In *Catalog 15*. Microswitch, August 1996, pp. 74–91.

Microswitch. "Temperature and Moisture Sensors." Microswitch. May 1997.

Microswitch. "Moisture Tutorial-Relative Humidity Sensors." In *Temperature and Moisture Sensors Catalog*. Microswitch, May 1997, pp. B1–B7.

Motorola Inc. "Analog to Digital Converter Resolution Extension Using a Motorola Pressure Sensor." Application note AN 1100. Motorola Inc., Sensor Device Data, DL200/D, Rev. 2, pp. 4-24 to 4-26, 1995.

Motorola Inc. "Sensor Device Data Book." DL 200/D, Rev. 2, Q2/95. Motorola Inc., 1995.

Quinnell, R. A. "Silicon Accelerometers Tackle Cost-Sensitive Applications." *EDN* (September 3, 1992), pp. 69–76.

Schultz, W. "Interfacing Semiconductor Pressure Sensors to Microcomputers." Application note AN-1318. Motorola Inc., Sensor Device Data, DL200/D, Rev. 2, pp. 4-99 to 4-108, 1995.

Steele, J. "Get Maximum Accuracy from Temperature Sensors." *Electronic Design* (August 19, 1996), pp. 99–110.

Swager, A. W. "Hall Effect Sensors-Improved ICs Find Broad Application." *EDN* (May 11, 1989), pp. 75–92.

Swartz, C., C. Derrington, and J. Gragg. "Temp X-ducer Pressure Sensor Element." Motorola AZ, USA.

Travis, B. "Smart-Sensor Standard Will Ease Net

Travis, B. "Temperature-Management ICs Comb pp. 38–48.

Walters, D. "Chemical Sensing: An Emergent M October 1996, pp. 173–186.

Winkler, C., and J. Baum. "Barometric Pressure sors." Application note AN-1326. Motorola Inc

Wood, T. "The Hall Effect Sensor." *Sensors* (Ma

Woods, S. P. "IEEE-P 1451.2 Smart Interface Mo Helmers Publishing Inc., pp. 25–46.

on Guide" (G 2112A). Analog Devices. Inc.
ty in Silicon Valley and Its Impact on Sensor Tech-
ber 1996. pp. 1–13.
ystem." Application note AN-1097. Motorola Inc.,
, pp. 4-19 to 4-23.
the Motorola MPX700 Series Differential Pressure
a Inc., Sensor Device Data, DL200/D, Rev. 2, pp. 4-

look. Dallas Semiconductor, TX, 1994–1995.
y in the MPX10 Series Pressure Transducer." Appli-
Device Data, DL200/D, Rev. 2, 1995, pp. 4-4 to

ms Technology. Japan: FiS Inc., 1996.
's Protect and Control." PCIM (November 1993),

allenge in Micromechanisms and Microelectricity."
mber 92CH3128-6), pp. 14–17.
ations. Englewood Cliffs, NJ: Prentice-Hall, 1991.
Pressure Sensors." Application note TN-002. IC

ure Sensors." Application note TN-001. IC Sensors,

ication note TN-010. IC Sensors, April 1995.
nology." Application note UATRO-9111. IC Sensors.

applications: A Cookbook Approach." *EDN* (January

Systems Using Fixed Components." *EDN* (July 6.

Signal Conditioning Amplifier Design for Sensor
otorola Inc., Sensor Device Data, DL200/D, Rev. 2,

ure Transducer in a Remote Sensing Application."
nc., MA, USA.
r Networks Sensors & Transducers." *Electronic De-*

ity out of Thermocouple Temperature Measurement
-274. Analog Devices, Inc., Norwood, MA, USA.
terface of MPX5100 Pressure Sensor with a Micro-
orola Inc., Sensor Device Data, DL200/D, Rev. 2,

Using the AD594/AD595." Application note AN-369.

nsors." In *Catalog 15*. Microswitch, August 1996,

rs." Microswitch, May 1997.
dity Sensors." In *Temperature and Moisture Sensors*
7.
lution Extension Using a Motorola Pressure Sensor."
sor Device Data, DL200/D, Rev. 2, pp. 4-24 to 4-26,

200/D, Rev. 2, Q2/95. Motorola Inc., 1995.
Cost-Sensitive Applications." *EDN* (September 3,

Sensors to Microcomputers." Application note AN-
200/D, Rev. 2, pp. 4-99 to 4-108, 1995.
perature Sensors." *Electronic Design* (August 19,

Cs Find Broad Application." *EDN* (May 11, 1989).

Swartz, C., C. Derrington, and J. Gragg. "Temperature Compensation Methods for the Motorola X-ducer Pressure Sensor Element." Motorola Application note AN 840. Motorola Inc., Phoenix, AZ, USA.

Travis, B. "Smart-Sensor Standard Will Ease Networking Woes." *EDN* (June 22, 1995), pp. 49–52.

Travis, B. "Temperature-Management ICs Combat System Meltdown." *EDN* (August 15, 1996), pp. 38–48.

Walters, D. "Chemical Sensing: An Emergent MEMS Technology." Proceedings of Sensors Expo, October 1996, pp. 173–186.

Winkler, C., and J. Baum. "Barometric Pressure Measurement Using Semiconductor Pressure Sensors." Application note AN-1326. Motorola Inc.

Wood, T. "The Hall Effect Sensor." *Sensors* (March 1986).

Woods, S. P. "IEEE-P 1451.2 Smart Interface Module." Proceedings of Sensors Expo, October 1996, Helmers Publishing Inc., pp. 25–46.

CHAPTER 8

Nonlinear Devices

8.1 Introduction

By exploiting the basic physics of semiconductor devices it is possible to design circuits that perform a wide variety of mathematical operations, including addition, subtraction, multiplication, and division as well as trigonometric, logarithmic, and exponential functions. Such circuits perform in the analog domain and frequently offer real advantages over more conventional digital computation. Operations where analog computation is preferable to digital include those where both the input and output signals must be analog, limited amounts of processing are required and no digital circuitry is present, the signal is differentiated to produce a rate signal, fast signals must be processed in real time, large dynamic ranges are involved, and complex or transcendental functions must be evaluated.

In an electronic design world, where a digital approach to design is preferred in many instances, much room remains for analog computation techniques, particularly in situations where a wide, dynamic range of signals or fast signals can be processed. To explain this situation, we take the case of a simple AC power meter. A simple AC power meter may be constructed very easily with a single analog multiplier as per Figure 8-1(a), where the moving coil meter can act as the integrator. A digital power meter would require conversion of both voltage and current to digital form, with considerable attention to the timing of the conversions, since the relative phase of the two signals is of critical importance. However, if with the advantage of a CPU (see Figure 8-1(b)) that has a display driven by it and a multiplexed ADC with spare capacity, the power metering facility could be added to the base system at minimal additional cost.

As another example, the first derivative of a varying analog signal is complex to calculate using digital techniques, compared to a simple C-R network for analog differentiation (Analog Devices, 1987, Section 5). Digitizing a signal with wide dynamic range also is expensive (see Figure 8-2). If such a signal is digitized

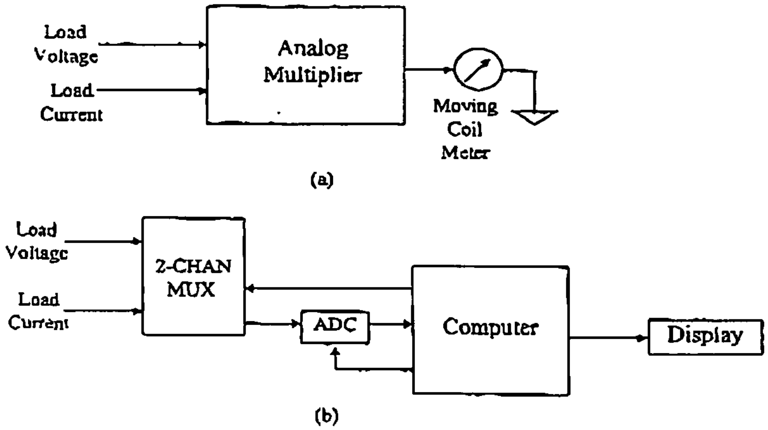


FIGURE 8-1 Power meter implementation: (a) analog approach, (b) digital approach

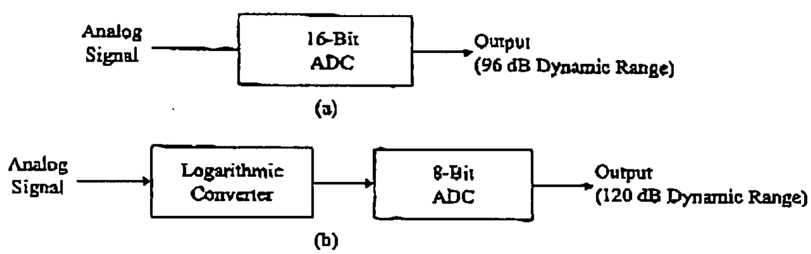


FIGURE 8-2 Analog processing advantage of signals with high dynamic range: (a) a 16-bit ADC, the expensive way, yielding a 96 dB dynamic range; (b) an inexpensive 8-bit ADC with a logarithmic converter, yielding a 120 dB dynamic range

with a 16-bit ADC (a comparatively expensive device), the ratio of an LSB to full scale is 96 dB; whereas if the signal were first applied to a logarithmic converter (frequently misnamed a *logarithmic amplifier*), then a dynamic range approaching 120 dB is practical with an 8-bit ADC.

Historically, analog computers have been slow devices. Even though high-frequency multipliers, modulators, logarithmic amplifiers, and other function generators have been available for many years, they generally have had relatively poor accuracy and stability and have not been considered analog computers. Within the last decade, a few classes of accurate nonlinear devices have entered the market: multipliers, modulators, and log amps (Analog Devices, 1990, Section 5). This chapter is an introduction to modern nonlinear devices, their design concepts, and special application areas.

8.2 A Basic Semiconductor ... to Analog Computatior

The operation of many analog co rithmic properties of silicon junctions. voltage relationship

$$I = I_0(\cdot$$

This could be rewritten as

$$V = \frac{kT}{q}\ln\left(\frac{I}{I_0} + \right.$$

where

I = the current through the di

k = Boltzman's constant (1.38

V = the voltage across the dio

q = a constant equal to unit ch

T = the absolute temperature i

I_0 = the extrapolated current fo

Referring to Figure 8-3, these equ diode increases exponentially with volt

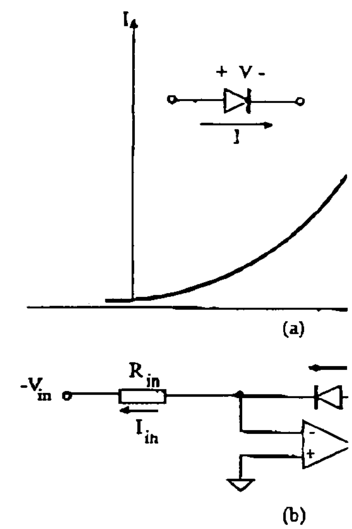
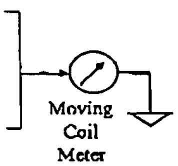
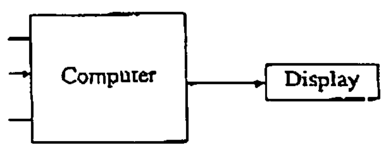
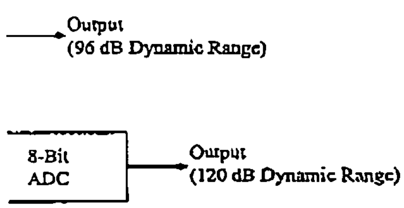


FIGURE 8-3 (a) Diode curve, (b) diode





ɪn: (a) analog approach, (b) digital approach



ge of signals with high dynamic range: (a)
a 96 dB dynamic range; (b) an inexpensive
ding a 120 dB dynamic range

pensive device), the ratio of an LSB to
nal were first applied to a logarithmic
ithmic amplifier), then a dynamic range
8-bit ADC.
: been slow devices. Even though high-
ırithmic amplifiers, and other function
ıy years, they generally have had rela-
'e not been considered analog computers.
accurate nonlinear devices have entered
log amps (Analog Devices, 1990, Sec-
) modern nonlinear devices, their design

8.2 A Basic Semiconductor Physics-Based Approach to Analog Computation Circuits

The operation of many analog computational circuits depends on the logarithmic properties of silicon junctions. An ideal logarithmic diode has the current voltage relationship

$$I = I_0(e^{qV/kT} - 1) \tag{8.1}$$

This could be rewritten as

$$V = \frac{kT}{q}\ln\left(\frac{I}{I_0}+1\right) \approx \frac{kT}{q}\ln\left(\frac{I}{I_0}\right) \tag{8.2}$$

where

I = the current through the diode;

k = Boltzman's constant (1.38062×10^{-23});

V = the voltage across the diode;

q = a constant equal to unit charge, 1.60219×10^{-19} coulombs;

T = the absolute temperature in Kelvin;

I_0 = the extrapolated current for $E_0 = V = 0$ volts.

Referring to Figure 8-3, these equations clearly show that the current in a diode increases exponentially with voltage or, conversely, the voltage increases

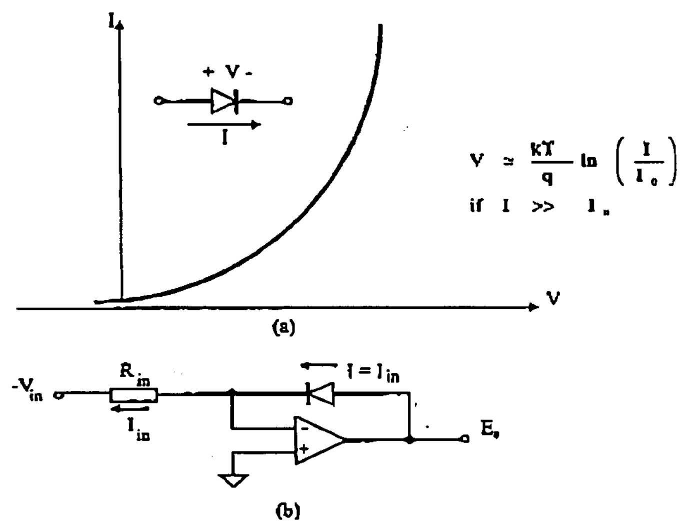


FIGURE 8-3 (a) Diode curve, (b) diode log converter

logarithmically with current. These equations are less clear in showing that I_0, the theoretical diode current at zero voltage, is temperature dependent and so the variation of a diode's behavior with temperature is by no means as simple as the equation would suggest; that is, the voltage is not proportional to absolute temperature at a fixed current. Several approximations concerning the logarithmic behavior of diodes are worth remembering:

$$\frac{kT}{q} = 26 \text{ mV(at } 28.58°\text{C)} \tag{8.3}$$

$$\frac{kT}{q} \ln_{10} = 60 \text{ mV(at } 29.25°\text{C)} \tag{8.4}$$

These approximations simplify the diode expression to

$$V = 60 \text{ mV} \log \frac{I}{I_0} \tag{8.5}$$

This simply says that V increases by 60 mV every time the current increases by a factor of 10 at 29.25°C.

If we were to place an ideal logarithmic diode in the feedback path (output to inverting input) of an operational amplifier and apply a current to the inverting input, the output voltage would be the logarithm of the input current times a temperature varying constant. For the circuit in Figure 8-3(b), if $I_{in} \gg I_0$,

$$E_0 = \frac{kT}{q} \ln\left(\frac{I_{in}}{I_0}\right) \approx 0.06 \log \frac{V_{in}}{R_{in} I_0} \tag{8.6}$$

It is unfortunate that real diodes are not ideal logarithmic diodes. In a real diode, the bulk resistivity, R_B, of the silicon limits the logarithmic accuracy at high currents and diffusion currents in surface inversion layers and generation-recombination effects in space-charge regions cause a scale factor error, m, at low currents. We therefore find that

$$E_0 = m\frac{kT}{q} \ln\left(\frac{I}{I_0}\right) + I_{RB} \tag{8.7}$$

where m varies with the current.

Even with similar diodes, m can vary (it is never less than 1 and may be as high as 4), as does the value of E_0 at which m changes. General purpose diodes therefore are impractical as logarithmic diodes for dynamic ranges of more than 100:1 (two decades).

Luckily, we can replace the diode with a grounded-base transistor as per Figure 8-4 and get a dynamic range of 1 million:1 (six decades) or more—the only disadvantage of such a circuit is that the signals can have only a single polarity.

From the Ebers and Moll equations (see Sheingold, 1976, for a detailed derivation), it may be shown that

$$E_0 = \frac{kT}{q} \ln\left(\frac{I_{in}}{I_{ES}}\right) - \frac{kT}{q} \ln \alpha_n \tag{8.8}$$

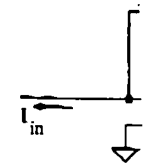


FIGURE 8-4 Transistor log converter

where $I_{in} \gg I_{ES}$; I_{ES} is the emitter
current-transfer ratio (α_n is not the gr
Since I_{ES} is less than a picoam
range of currents, in the silicon planar
converters, the effect of the second te
equation simplifies to

$$E_0 = \frac{k}{q}$$

Such logarithmic converters are
kT/q has a temperature coefficient of 0
every 10°C temperature rise and varie
these basic concepts, in refined forms c
circuits, are used in nonlinear circuits.
techniques, see Analog Devices, Inc.,

8.3 Important Design Consi

In the discussion of nonlinear dev
are the dynamic range of a signal and

8.3.1 Dynamic Range

In many cases, a wide dynamic
something to be preserved at all costs.
quality reproduction of music and com
signal must be compressed to a smalle
mation. Compression is used in magn
the dynamic range is limited by tape sa
ularity of the medium. In professional
"undone" by precisely matched nonline
techniques are used in conveying speec
mance more likely is to be measured ir
fidelity. The reciprocal processes of com

ıtions are less clear in showing that I_0, .ge, is temperature dependent and so the ɑperature is by no means as simple as voltage is not proportional to absolute ɔroximations concerning the logarithmic ɿg:

V(at 28.58°C) (8.3)

V(at 29.25°C) (8.4)

expression to

$$\text{V} \log \frac{I}{I_0} \tag{8.5}$$

60 mV every time the current increases

nic diode in the feedback path (output to ier and apply a current to the inverting logarithm of the input current times a cuit in Figure 8-3(b), if $I_{in} \gg I_0$,

$$\approx 0.06 \log \frac{V_{in}}{R_{in} I_0} \tag{8.6}$$

: not ideal logarithmic diodes. In a real icon limits the logarithmic accuracy at urface inversion layers and generation- ɡions cause a scale factor error, m, at

$$\left(\frac{I}{I_0}\right) + I_{RB} \tag{8.7}$$

y (it is never less than 1 and may be as ich m changes. General purpose diodes liodes for dynamic ranges of more than

with a grounded-base transistor as per million:1 (six decades) or more—the hat the signals can have only a single

s (see Sheingold, 1976, for a detailed

$$\left.\right) - \frac{kT}{q} \ln \alpha_n \tag{8.8}$$

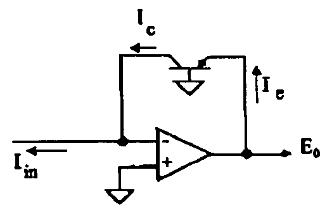


FIGURE 8-4 Transistor log converter

where $I_{in} \gg I_{ES}$; I_{ES} is the emitter saturation current; and α_n is the forward current-transfer ratio (α_n is not the grounded-base current gain).

Since I_{ES} is less than a picoampere and α_n is nearly unity over a wide range of currents, in the silicon planar transistors used to manufacture logarithmic converters, the effect of the second term generally may be disregarded; and the equation simplifies to

$$E_0 = \frac{kT}{q} \ln\left(\frac{I_{in}}{I_{ES}}\right) \tag{8.9}$$

Such logarithmic converters are temperature sensitive. In equation (8.9), kT/q has a temperature coefficient of 0.34%/°C around 25°C, and I_{ES} doubles for every 10°C temperature rise and varies with device size and geometry. Many of these basic concepts, in refined forms or in combination with other compensation circuits, are used in nonlinear circuits. (For a further discussion on these basic techniques, see Analog Devices, Inc., 1987; Sheingold 1976.)

8.3 Important Design Considerations in Nonlinear Devices

In the discussion of nonlinear devices two important design considerations are the dynamic range of a signal and the noise.

8.3.1 Dynamic Range

In many cases, a wide dynamic range is an essential aspect of a signal, something to be preserved at all costs. This is true, for example, in the high-quality reproduction of music and communication systems. However, often the signal must be compressed to a smaller range with no significant loss of information. Compression is used in magnetic recording, where the upper end of the dynamic range is limited by tape saturation and the lower end by the granularity of the medium. In professional noise-reduction systems, compression is "undone" by precisely matched nonlinear expansion during reproduction. Similar techniques are used in conveying speech over noisy channels, where the performance more likely is to be measured in terms of word intelligibility than audio fidelity. The reciprocal processes of compressing and expanding are implemented

using "compandors," and many schemes have been devised to achieve this function. In terms of the signal voltage,

$$\text{Dynamic range (dB)} = 20\log_{10}\frac{\text{Largest signal voltage}}{\text{Smallest signal voltage}} \tag{8.10}$$

Note that in a linear-impedance system, the power is proportional to the signal voltage (or current) squared. Accordingly,

$$\text{Dynamic range (dB)} = 10\log_{10}\frac{\text{Largest signal power}}{\text{Smallest signal power}} \tag{8.11}$$

Also, it is useful to differentiate between the dynamic range of the signal and that of the processing system. The signal dynamic range is

$$\text{Signal dynamic range} = 20\log_{10}\frac{\text{Largest actual signal voltage}}{\text{Smallest actual signal voltage}} \tag{8.12}$$

whereas the system dynamic range is

$$\text{System dynamic range} = 20\log_{10}\frac{\text{Largest permissible signal voltage}}{\text{Smallest detected signal voltage}} \tag{8.13}$$

In system design, one should be concerned with the system's dynamic range, which should match or exceed the signal dynamic range.

8.3.2 Noise Limitations

The dynamic range of all signal-processing systems is limited by random noise, which sets a fundamental bound on the smallest signal that can be detected or otherwise utilized with an adequate signal-to-noise ratio (SNR). This noise may be generated by numerous mechanisms, including those associated with the source itself (e.g., antenna, photomultiplier, piezoelectric transducer) as well as by the active and passive devices in the amplifiers.

Noise cannot be discussed without reference to bandwidth, which will be unavoidably limited by the types of amplifier used. Deliberate filtering often is included in a signal-processing channel to reduce noise, as well as to improve the separation of wanted from unwanted signals. This may take the form of bandpass, low-pass, or high-pass functions or combinations of these, depending on the situation. Nonlinear filtering also may be used, for example, to minimize the disturbance of the signal path in the presence of impulsive noise.

The noise powers of uncorrelated sources add up, so noise voltages (or currents) must be added using a root-sum-of-squares (RSS) calculation. This leads to some rather startling consequences. Suppose a system has a major voltage noise source of magnitude E_a and several minor noise sources whose RSS sum to a magnitude of E_b. Then, E_a needs to be only twice E_b for the major source to contribute almost 90% of the total system noise. When $E_a/E_b = 5$, 98% of the noise is due to E_a.

It follows that the overall noise
greatly by (i) minimizing the input-
the highest possible gain in this sta
frequently cannot be realized in sy
dynamic range, because the high ga
at maximum signal levels.

Noise frequently is specified in
The term reflects the fact that the
the system's noise bandwidth, B_N (
interest in specifying a channel's in
the noise bandwidth is not equal to
the bandwidth of an equivalent syste
at that frequency. A system with a s
has a B_N value equal to $\pi f_0/2$, or
pass sections in cascade, B_N is $\pi f_0/$
both voltage and current component
the square of either the voltage or cu
dimensions of volts/$\sqrt{\text{Hz}}$ and amps/
Noise signals usually are small
negligible. In such circumstances, it is
evaluate each contributing source ind
to calculate the total noise. A notab
where even very small noise voltage
later stages in the amplifier. Special a
specification are required in such case

For details on noise performanc
Section 2.3.2 of Chapter 2. While nois
range, performance at the upper end o
importance of nonlinear aspects of ci

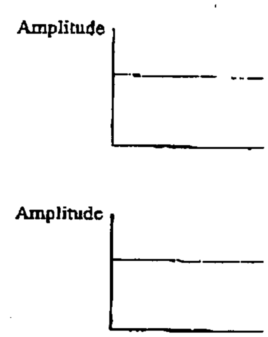


FIGURE 8-5 Filter noise bandwidths:
$1.57 f_0$), (b) two single-pole low-pass filte

have been devised to achieve this func-

$$\frac{\text{Largest signal voltage}}{\text{Smallest signal voltage}} \quad (8.10)$$

stem, the power is proportional to the
·rdingly,

$$\frac{\text{Largest signal power}}{\text{Smallest signal power}} \quad (8.11)$$

·tween the dynamic range of the signal
ignal dynamic range is

$$\frac{\text{argest actual signal voltage}}{\text{nallest actual signal voltage}} \quad (8.12)$$

$$\frac{\text{gest permissible signal voltage}}{\text{allest detected signal voltage}} \quad (8.13)$$

:erned with the system's dynamic range,
l dynamic range.

·ocessing systems is limited by random
ı the smallest signal that can be detected
signal-to-noise ratio (SNR). This noise
sms, including those associated with the
lier, piezoelectric transducer) as well as
amplifiers.
reference to bandwidth, which will be
plifier used. Deliberate filtering often is
to reduce noise, as well as to improve
ed signals. This may take the form of
ıns or combinations of these, depending
may be used, for example, to minimize
presence of impulsive noise.
sources add up, so noise voltages (or
sum-of-squares (RSS) calculation. This
es. Suppose a system has a major voltage
:al minor noise sources whose RSS sum
o be only twice E_b for the major source
ystem noise. When $E_a/E_b = 5$, 98% of

It follows that the overall noise performance of a practical system can benefit greatly by (i) minimizing the input-referred noise of the first stage and (ii) using the highest possible gain in this stage. However, the second of these objectives frequently cannot be realized in systems that must handle signals of a large dynamic range, because the high gain would preclude distortion-free operation at maximum signal levels.

Noise frequently is specified in terms of a noise spectral density (NSD). The term reflects the fact that the total noise power is directly proportional to the system's noise bandwidth, B_N (in Hertz). The NSD therefore usually is of interest in specifying a channel's input-noise limitations. Note that, in general, the noise bandwidth is not equal to the -3dB bandwidth. B_N can be viewed as the bandwidth of an equivalent system with a "brick-wall" cessation of response at that frequency. A system with a single-pole low-pass corner at $f_0 = 1/2\pi T$ has a B_N value equal to $\pi f_0/2$, or $1.57 f_0$, while for two such real pole low-pass sections in cascade, B_N is $\pi f_0/4$ (see Figure 8-5). The total NSD will have both voltage and current components. Since the noise power is proportional to the square of either the voltage or current, these two noise components have the dimensions of volts/$\sqrt{\text{Hz}}$ and amps/$\sqrt{\text{Hz}}$.

Noise signals usually are small, and therefore nonlinear effects often are negligible. In such circumstances, it is permissible to use superposition methods to evaluate each contributing source independently, followed by an RSS calculation to calculate the total noise. A notable exception is the logarithmic amplifier, where even very small noise voltages at the input can cause heavy limiting in later stages in the amplifier. Special approaches to both noise analysis and noise specification are required in such cases.

For details on noise performance, see Analog Devices, Inc. (1992a) and Section 2.3.2 of Chapter 2. While noise limits the low end of a system's dynamic range, performance at the upper end of signal range is degraded by the increasing importance of nonlinear aspects of circuit behavior.

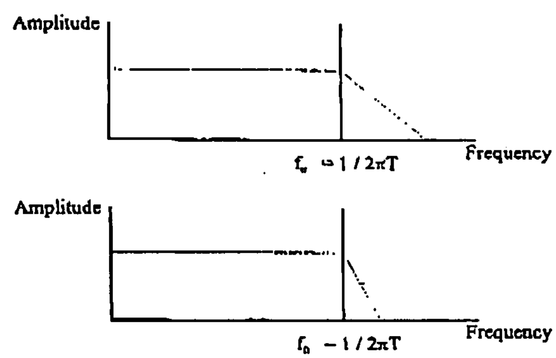


FIGURE 8-5 Filter noise bandwidths: (a) single-pole low-pass filter ($B_N = \pi f_0/2 = 1.57 f_0$), (b) two single-pole low-pass filters sections in cascade ($B_N = \pi f_0/4$)

8.4 Logarithmic Converters

The conversion of a signal to its equivalent logarithmic value involves a nonlinear operation, the consequences of which can be confusing if not fully understood. It is important to realize that many of the familiar concepts of linear circuits are irrelevant to log amps. For example, the incremental gain of an ideal log amp approaches infinity as the input tends to 0, and change of offset at the output of a log amp is equivalent to a change of amplitude at its input, not a change of input offset. The commonly used term *logarithmic amplifier* is something of a misnomer but is used lavishly.

If we consider the equation $y = \log(x)$, as shown in Figure 8-6(a), every time x is multiplied by a constant A, y increases by another constant A_1. Thus, if $\log(K) = K_1$, then $\log(AK) = K_1 + A_1$; $\log(A^2K) = K_1 + 2A_1$; $\log(K/A) = K_1 - A_1$. As shown in figure 8.6(a) when x is 1, y approaches 0.

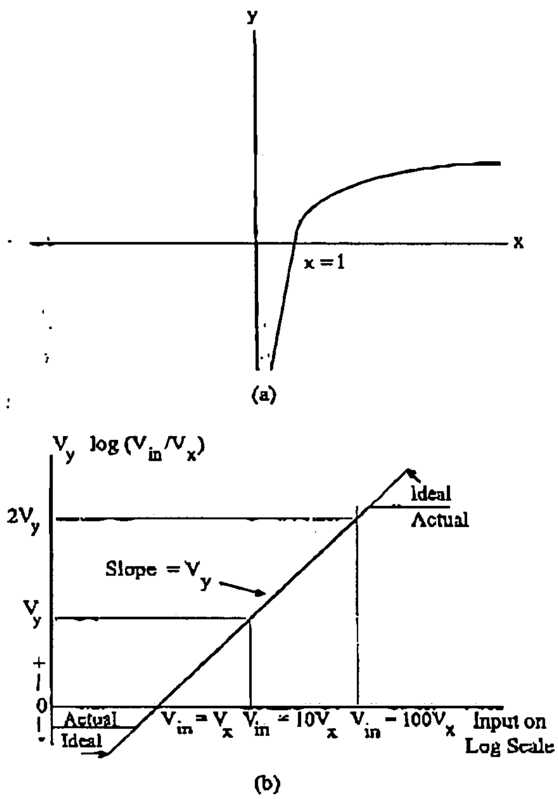


FIGURE 8-6 (a) Graph of $y = \log(x)$, (b) log amp transfer function

A practical log amp has the
Figure 8-6(b). Such a practical log a

$V_{out} = 1$

This is valid over some range o
(40 dB) to over 1 million:1 (120 dB)
is logarithmic, and the ideal transfer
V_x, the logarithm is 0 (log 1 = 0). V_y
of the log amp, because the graph cro

With inputs very close to 0, log
most then follow a linear V_{in}/V_{out}
noise. Noise often limits the dynami
the dimensions of voltage, because
divided by a voltage, V_x, because the
dimensionless ratio.

8.4.1 Practical Log Amps

The logarithm function is indete
can respond to negative inputs in thr

1. They can give a full-scale negati
   basic log amp saturates with nega
2. They can give an output proportio
   input and disregard its sign, as sho
   can be considered a full-wave det
   often is referred to as a *detecting l*
3. They can give an output proportio
   input and have the same sign as the
   of log amp can be considered a vi
   and may be known as a *logarithmic*
   a *true log amp.*

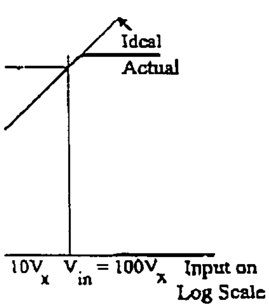
8.4.2 Practical Implement

Three basic architectures are used
Inc.: the basic diode log amp, the true
amp.

8.4.2.1 The Basic Diode Lo

As per the discussion in Section
amp function (see Figure 8-3). In pract
is limited to 40–60 dB because of non
if the diode is replaced with a diode co
the dynamic range can be extended to

quivalent logarithmic value involves a
f which can be confusing if not fully
many of the familiar concepts of linear
ample, the incremental gain of an ideal
it tends to 0, and change of offset at
o a change of amplitude at its input,
nly used term *logarithmic amplifier* is
ishly.
g(x), as shown in Figure 8-6(a), every
ncreases by another constant A_1. Thus,
$_1$; $\log(A^2K) = K_1 + 2A_1$; $\log(K/A) =$
1 x is 1, y approaches 0.



) log amp transfer function

A practical log amp has the graph of transfer characteristics shown in Figure 8-6(b). Such a practical log amp has the transfer function

$$V_{out} = V_y \log_{10}\left(\frac{V_{in}}{V_x}\right) \tag{8.14}$$

This is valid over some range of input values, which may vary from 100:1 (40 dB) to over 1 million:1 (120 dB). The scale of the horizontal axis (the input) is logarithmic, and the ideal transfer characteristic is a straight line. When $V_{in} = V_x$, the logarithm is 0 ($\log 1 = 0$). V_x therefore is known as the *intercept voltage* of the log amp, because the graph crosses the horizontal axis at this value of V_{in}.

With inputs very close to 0, log amps cease to behave logarithmically and most then follow a linear V_{in}/V_{out} law. This behavior often is lost in device noise. Noise often limits the dynamic range of a log amp. The constant V_y has the dimensions of voltage, because the output is a voltage. The input, V_{in}, is divided by a voltage, V_x, because the argument of a logarithm must be a simple dimensionless ratio.

8.4.1 Practical Log Amps and Negative Values of x

The logarithm function is indeterminate for negative values of x. Log amps can respond to negative inputs in three different ways:

1. They can give a full-scale negative output as shown in Figure 8-7(a). This basic log amp saturates with negative inputs.
2. They can give an output proportional to the log of the absolute value of the input and disregard its sign, as shown in Figure 8-7(b). This type of log amp can be considered a full-wave detector with a logarithmic characteristic and often is referred to as a *detecting log amp*.
3. They can give an output proportional to the log of the absolute value of the input and have the same sign as the input, as shown in Figure 8-7(c). This type of log amp can be considered a video amp with a logarithmic characteristic and may be known as a *logarithmic video* (log video) *amplifier* or, sometimes, a *true log amp*.

8.4.2 Practical Implementation

Three basic architectures are used by manufacturers such as Analog Devices, Inc.: the basic diode log amp, the true log amp, and the successive detection log amp.

8.4.2.1 The Basic Diode Log Amp

As per the discussion in Section 8.2, a simple diode could be used for a log amp function (see Figure 8-3). In practice, the dynamic range of this configuration is limited to 40–60 dB because of nonideal characteristics of the diode. However, if the diode is replaced with a diode connected transistor, as shown in Figure 8-4, the dynamic range can be extended to 120 dB or more. This type of log amp has

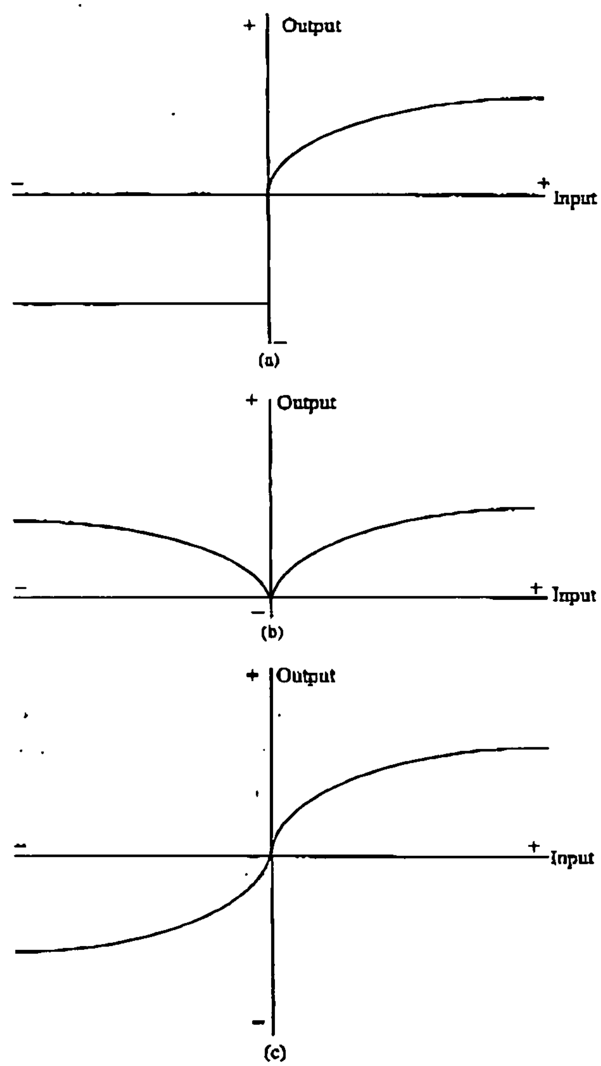


FIGURE 8-7 Log amps with negative values of x input; (a) basic log amp, (b) detecting log amp, (c) true log amp or log video amp

three disadvantages: both the slope and intercept are temperature dependent, it will handle only unipolar signals, and its bandwidth is both limited and dependent on the signal amplitude. Where several such log amps are used on a single chip to produce an analog computer that performs both log and antilog operations, the temperature variation in the log operations is unimportant, since it is compensated

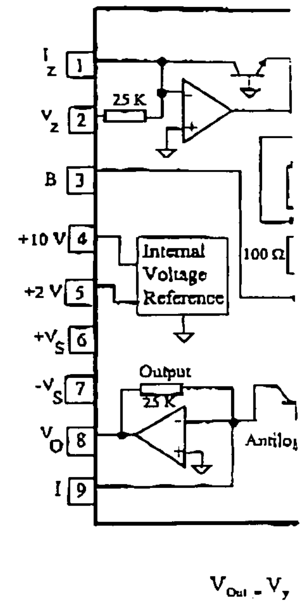


FIGURE 8-8 The AD-538 analog c
Analog Devices, Inc.)

for by a similar variation in the ant
that utilizes such techniques is the A
Analog Devices, Inc. (Figure 8-8). T
$V_{out} = V_y(V_z/V_x)$ can multiply, divi
is required, these types of devices re
1976).

A major disadvantage of this typ
is its limited frequency response, lir
feedback capacitance of these devic
limits are within a few hundred kHz.
detecting and true log architectures a

8.4.2.2 True and Detectin

Although these two types differ
design is the same: Instead of one a
these designs use a number of similar
large signal behavior.

As shown in Figure 8-9(a) cor
output of each driving a summing
amplifier has a gain of A dB, the s

ut

+ Input

t

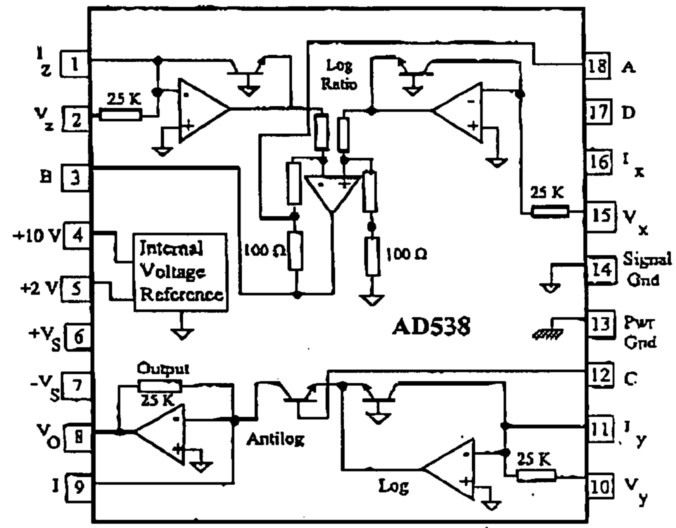
+ Input

t

+ Input

es of x input: (a) basic log amp, (b) detect-
ip

ntercept are temperature dependent, it
andwidth is both limited and dependent
ich log amps are used on a single chip
ms both log and antilog operations, the
is unimportant, since it is compensated



$$V_{Out} = V_y \left[\frac{V_z}{V_x}\right]^m$$

FIGURE 8-8 The AD-538 analog computational unit. (Reproduced by permission of Analog Devices, Inc.)

for by a similar variation in the antilogging. An example of a practical device that utilizes such techniques is the AD-538 analog computation unit (ACU) from Analog Devices, Inc. (Figure 8-8). This device, which has a transfer function of $V_{out} = V_y(V_z/V_x)$ can multiply, divide, and raise to powers. When actual logging is required, these types of devices require temperature compensation (Sheingold, 1976).

A major disadvantage of this type of log amp for high-frequency applications is its limited frequency response, limited by Miller capacitance or the residual feedback capacitance of these devices (Analog Devices, Inc., 1995). Practical limits are within a few hundred kHz. Therefore, for high-frequency applications detecting and true log architectures are used.

8.4.2.2 True and Detecting Log Amps

Although these two types differ in detail, the general principle behind their design is the same: Instead of one amplifier having a logarithmic characteristic, these designs use a number of similar, cascaded linear stages having well-defined large signal behavior.

As shown in Figure 8-9(a) consider N cascaded limiting amplifiers, the output of each driving a summing circuit as well as the next stage. If each amplifier has a gain of A dB, the small signal gain of the strip is NA dB. If

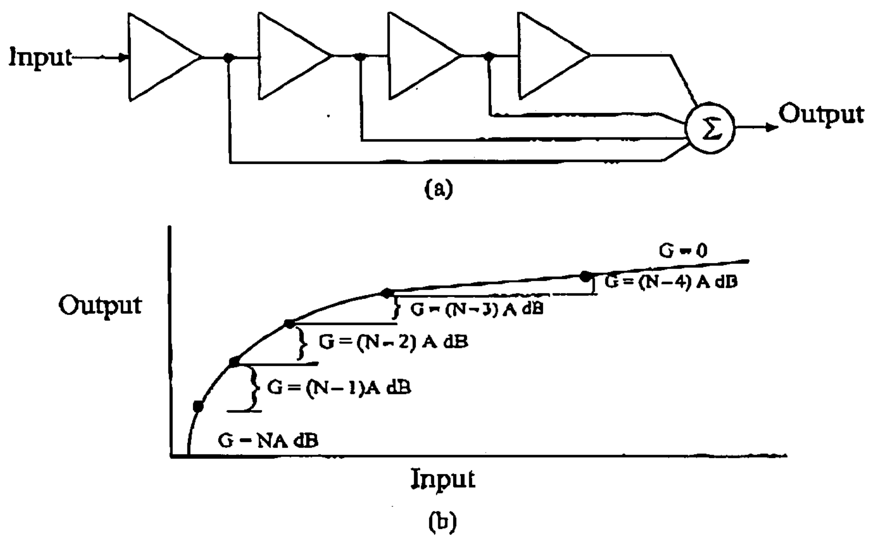


FIGURE 8-9 Multistage log amp: (a) architecture, (b) response for unipolar case

the input signal is small enough for the last stage not to limit, the output of the summing amplifier will be dominated by the output of the last stage. As the input signal increases, the last stage will limit. It now will make a fixed contribution to the output of the summing amplifier, but the incremental gain to the summing amplifier will drop to $(N-1)A$ dB. As the input continues to increase, this stage in turn will limit and make a fixed contribution to the output, and the incremental gain will drop to $(N-2)A$ dB, and so forth, until the first stage limits and the output ceases to change with increasing signal input.

The response curve therefore is a set of straight lines, as shown in Figure 8-9(b). The total of these lines, though, is a very good approximation to a logarithmic curve and, in practice, is an even better one, because few limiting amplifiers, especially high-frequency ones, limit quite as abruptly as this model assumes. Due to the compromise needed between log approximation and number of gain stages, gains of 10–12 dB are chosen in practical devices (Analog Devices, 1995).

This general model, which is ideal, becomes difficult to implement at high frequencies due to delays associated with each stage. If each stage has a delay of t ns, a signal that passes through all stages will have a delay of Nt ns compared to a signal that passes only one stage, which is delayed by only t ns. Some solutions for such difficulties are discussed in Analog Devices (1995). Multistage architectures such as these or their variations are video log amps or true log amps. However, the most common types of high-frequency log amps are the devices based on successive detection architecture.

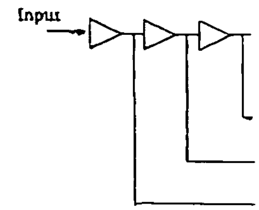


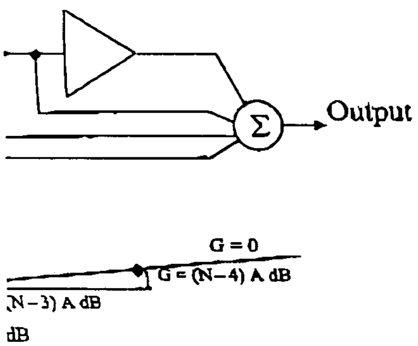
FIGURE 8-10 Successive detection l

8.4.2.3 Successive Detectic

The successive detection log am
described previously, but instead of su
are applied to detectors, and the de
Figure 8-10. If the detectors have cu
involve no more than connecting all t
Log amps using this architecture
and a limiting output. In many applic
in some (FM receivers with "S" mete
log output of a successive detection l
information, and the phase and freque
In the past, it has been necess
frequency successive detection log am
amplifiers. These typically are assembl
advances in IC processes have allowe
on a single chip.
The AD-640 log amp from Anal
detection type log amp for high-frequ
five limiting stages (10 dB per stage) a
package, and its logarithmic performan
diagram of AD-640 is shown in Figure
With reference to Figure 8-11(b),
tion where V_x is calibrated to 1 mV
proportional to V_y. Base 10 logarithm
relationship to decibel values. For V_{in}
so the output voltage is V_y. At $V_{in} =$
therefore can be viewed either as the
factor.
The AD-640 conforms to equatio
the form of current rather than voltage:

$$I_{out} = I_y \ldots$$

Each of the five stages in the AD-
detected output. The transfer function



chitecture, (b) response for unipolar case

last stage not to limit, the output of the
the output of the last stage. As the input
. It now will make a fixed contribution
out the incremental gain to the summing
he input continues to increase, this stage
bution to the output, and the incremental
forth, until the first stage limits and the
signal input.
a set of straight lines, as shown in
though, is a very good approximation
e, is an even better one, because few
uency ones, limit quite as abruptly as
nise needed between log approximation
−12 dB are chosen in practical devices

becomes difficult to implement at high
n each stage. If each stage has a delay of
ges will have a delay of Nt ns compared
which is delayed by only t ns. Some
ed in Analog Devices (1995). Multistage
ons are video log amps or true log amps.
igh-frequency log amps are the devices
re.

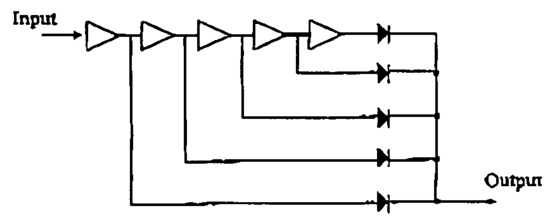


FIGURE 8-10 Successive detection logarithmic amplifier

8.4.2.3 Successive Detection Log Amps

The successive detection log amp consists of cascaded limiting stages as described previously, but instead of summing their outputs directly, these outputs *are applied to detectors, and the detector outputs are summed as shown in Figure 8-10. If the detectors have current outputs, the summing process may involve no more than connecting all the detector outputs.*

Log amps using this architecture have two types of output: the log output and a limiting output. In many applications, the limiting output is not used, but in some (FM receivers with "S" meters, for example) both are necessary. The log output of a successive detection log amplifier generally contains amplitude information, and the phase and frequency information is lost.

In the past, it has been necessary to construct high-performance, high-frequency successive detection log amps using a number of individual limiting amplifiers. These typically are assembled in complex and costly hybrids. Recent advances in IC processes have allowed this complete function to be integrated on a single chip.

The AD-640 log amp from Analog Devices is an example of successive detection type log amp for high-frequency use. The AD-640 log amp contains five limiting stages (10 dB per stage) and five full-wave detectors in a single IC package, and its logarithmic performance extends from DC to 145 MHz. A block diagram of AD-640 is shown in Figure 8-11.

With reference to Figure 8-11(b), the AD-640 has its log amp transfer function where V_x is calibrated to 1 mV exactly. The slope of the line is directly proportional to V_y. Base 10 logarithms are used in this context to simplify the relationship to decibel values. For $V_{in} = 10V_x$, the logarithm has a value of 1, so the output voltage is V_y. At $V_{in} = 100V_x$, the output is $2V_y$, and so on. V_y therefore can be viewed either as the slope voltage or as the volts per decade factor.

The AD-640 conforms to equation (8.1) except that its two outputs are in the form of current rather than voltage:

$$I_{out} = I_y \log(V_{in}/V_x) \tag{8.15}$$

Each of the five stages in the AD-640 has a gain of 10 dB and a full-wave detected output. The transfer function of the device is shown in Figure 8-11(b)

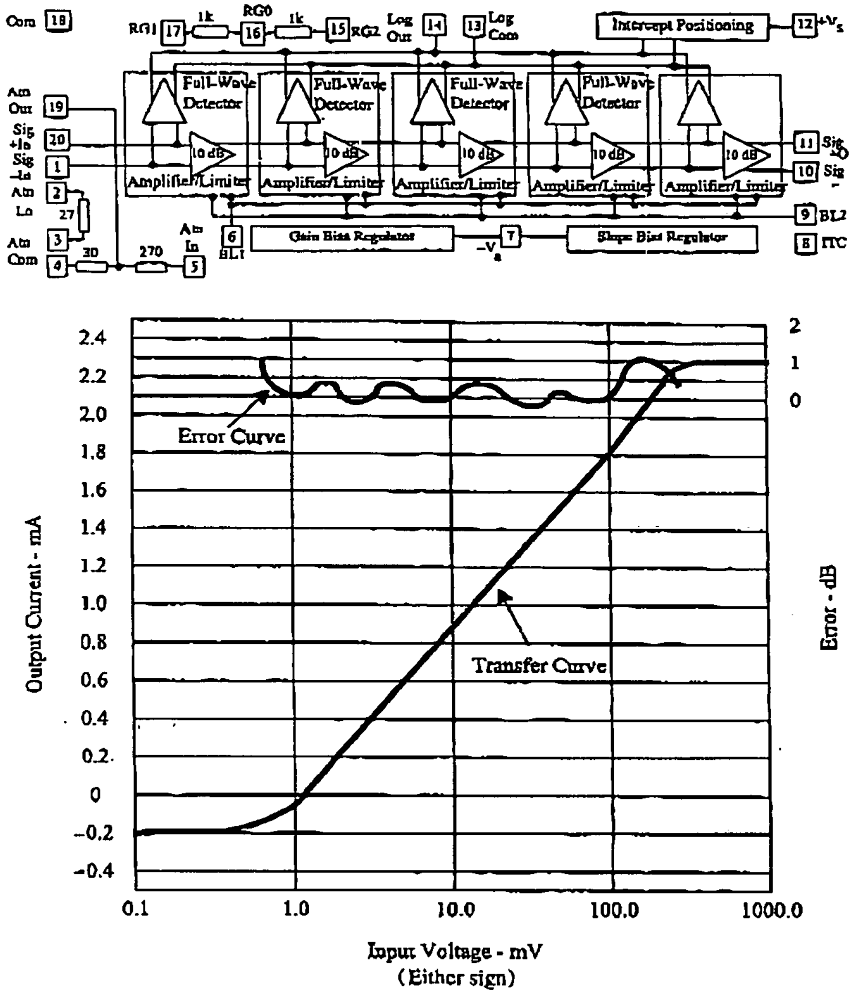


FIGURE 8-11 The AD-640 log amp: (a) block diagram, (b) transfer function and error curve. (Reproduced by permission of Analog Devices, Inc.)

along with the error curve. Note the excellent log linearity over an input range of 1–100 mV (40 dB). Although well suited to RF applications, the AD-640 is DC coupled throughout. This allows it to be used in low-frequency and very low-frequency systems, including audio measurements, sonar, and other instruments requiring operation to low frequencies or even DC. Unlike many other log amps, the AD-640 is laser trimmed to a high absolute accuracy of both slope and intercept and is fully temperature compensated. Some key features of the AD-640 are

1. 45 dB dynamic range; two can cas
2. Bandwidth DC to 145 MHz (120 l
3. Slope of 1 mA/decade, temperatur
4. Less than 1 dB log nonlinearity.
5. Balanced circuitry for stability and

For further details on applications

8.4.3 Key Parameters of L

In selecting log amps for a given ered are listed in Table 8-1.

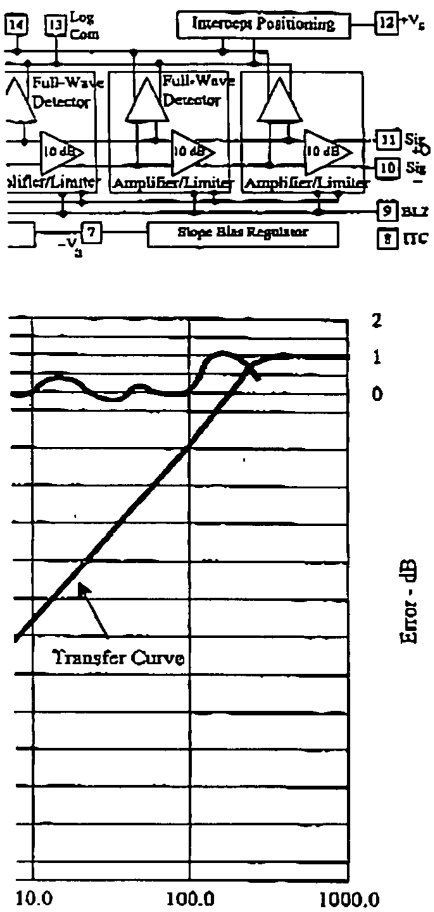
Over the years, logarithmic ampli ment of terms, some quite misleadin attempts to classify log amps into t and application domain and try to be nomenclature. For details, see Analog

TABLE 8-1 Key parameters of

Parameter	
Noise	Noise referr may be e density (voltage (
Dynamic range	Range of sig logarithm
Frequency response	Range of fre correctly
Slope	Gradient of
Intercept point	Value of inp
Log linearity	Deviation of axes) fro

TABLE 8-2 Types of log amps an sion of Analog Devices, Inc.)

Type	
Translinear log amps	Based on bipolar perform
Baseband log amps	Respond to input, used, s amp" a input
Demodulating log amps	AC input envelop *detecti*



olmge - mV
ıer sign)

a) block diagram, (b) transfer function and ınalog Devices, Inc.)

:llent log linearity over an input range of d to RF applications, the AD-640 is DC : used in low-frequency and very low- surements, sonar, and other instruments ' even DC. Unlike many other log amps, ı absolute accuracy of both slope and :nsated. Some key features of the AD-

1. 45 dB dynamic range, two can cascade to 95 dB.
2. Bandwidth DC to 145 MHz (120 MHz when cascaded).
3. Slope of 1 mA/decade, temperature stable.
4. Less than 1 dB log nonlinearity.
5. Balanced circuitry for stability and minimal external components.

For further details on applications, see Analog Devices (1992a, 1992c, 1995).

8.4.3 Key Parameters of Log Amps and Classifications

In selecting log amps for a given application, key parameters to be considered are listed in Table 8-1.

Over the years, logarithmic amplifiers have accumulated a confusing assortment of terms, some quite misleading. Here (Table 8-2), Analog Devices, Inc. attempts to classify log amps into three broad groups according to structure and application domain and try to be consistent in matters of terminology and nomenclature. For details, see Analog Devices (1992a, Section 9).

TABLE 8-1 Key parameters of log amps

Parameter	*Description*
Noise	Noise referred to the input (RTI) of the log amp, which may be expressed as a noise figure, as noise spectral density (voltage, current, or both), or as noise voltage (or noise current or both)
Dynamic range	Range of signal over which the amplifier behaves in a logarithmic manner (expressed in decibels)
Frequency response	Range of frequencies over which the log amp functions correctly
Slope	Gradient of transfer characteristic in V/dB or mA/dB
Intercept point	Value of input signal at which output is 0
Log linearity	Deviation of transfer characteristic (plotted on log/line axes) from a straight line (expressed in decibels)

TABLE 8-2 Types of log amps and their behavior. (Reproduced by permission of Analog Devices, Inc.)

Type	*Performance*
Translinear log amps	Based on logarithmic (or translinear) properties of bipolar transistors: wide dynamic range, poor AC performance
Baseband log amps	Respond to instantaneous value of rapidly changing input, "progressive compression technique" often used, sometimes called *video log amps*, "true log amp" accepts bipolar inputs sign of output following input
Demodulating log amps	AC input signal is rectified, output is the modulated envelope of the input, often called *successive detection log amp*

8.5 Multipliers and Dividers

A multiplier is a device having two input ports and an output port. The signal at the output is the product of the two input signals. If both input and output signals are voltages, the transfer characteristic is the product of the two voltages divided by a scaling factor, K, which has the dimension of voltage (see Figure 8-12(a)). From a mathematical point of view, multiplication is a four-quadrant operation; that is to say, both inputs may be either positive or negative, as may be the output. Some of the circuits used to produce electronic multipliers, however, are limited to signals of one polarity. If both signals must be unipolar, we have a single-quadrant multiplier and the output also is unipolar. If one of the signals is unipolar, but the other may have either polarity, the multiplier is a two-quadrant multiplier and the output may have either polarity (and is bipolar). The circuitry used to produce one- and two-quadrant multipliers may be simpler than that required for four quadrant multipliers; and since in many applications full four-quadrant multiplication is not required, it is common to find accurate devices that work only in one or two quadrants.

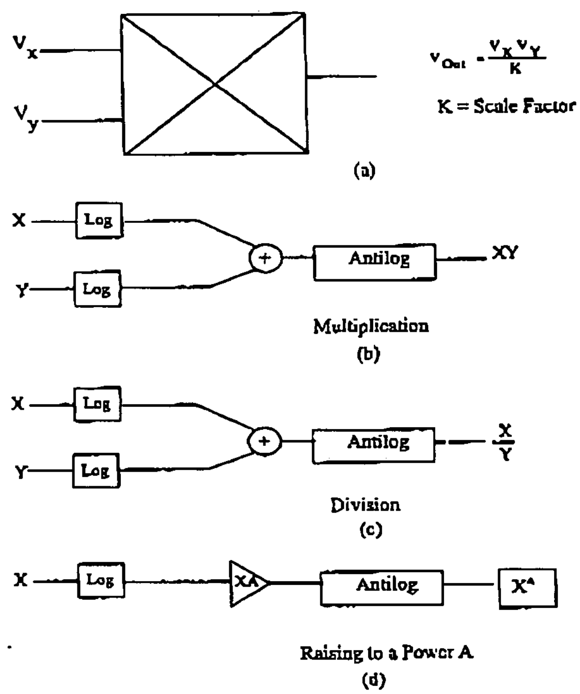


FIGURE 8-12 Analog multiplier: (a) basic block diagram, (b) multiplication, (c) division, (d) raising to a power A

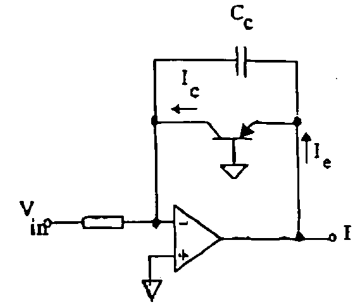


FIGURE 8-13 Log converter compen

Many techniques can be used for discussed in Sheingold (1976). Most circuits or the use of a Gilbert cell ((Analog Devices is such a monolithic i

Some disadvantages of such circu of its bandwidth with the signal ampli arises from the variation of emitter re base transistor. With reference to Fig the emitter current, being approximat circuit is inversely proportional to the compensation capacitor or merely str to the transistor current. Therefore, i 120 dB dynamic range, its bandwidth inconvenient. For details, see Analog I

In addition to adopting other imp a popular technique used in commerci There is a linear relationship between transistor and its transconductance (gai

$$\frac{dI_c}{dV_{BE}}$$

where

I_c = collector curre

V_{BE} = base-emitter vo

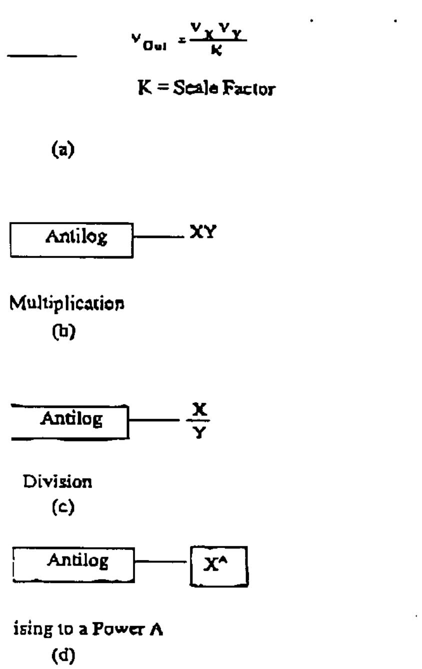
q = electron charge

k = Boltzmann's co

$q/kT = 1/(25.69\ \text{mV})$

This relationship may be exploited pair of silicon transistors (Analog De

o input ports and an output port. The e two input signals. If both input and characteristic is the product of the two which has the dimension of voltage (see oint of view, multiplication is a four- puts may be either positive or negative, used to produce electronic multipliers, larity. If both signals must be unipolar, l the output also is unipolar. If one of have either polarity, the multiplier is a ay have either polarity (and is bipolar). vo-quadrant multipliers may be simpler ipliers; and since in many applications equired, it is common to find accurate drants.



: block diagram, (b) multiplication, (c) di-

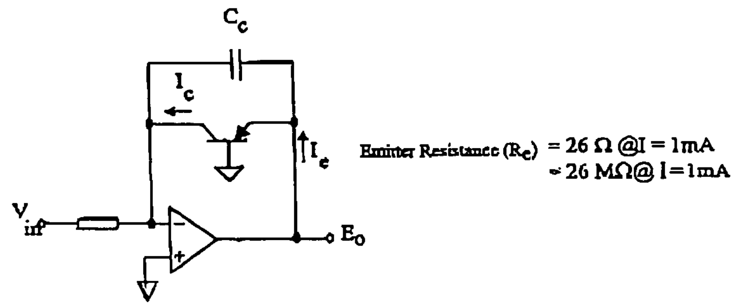


FIGURE 8-13 Log converter compensation problem

Many techniques can be used for analog multipliers, and some of these are discussed in Sheingold (1976). Most common forms are the use of log/antilog circuits or the use of a Gilbert cell (Gilbert, 1968a, 1968b). The AD-538 from Analog Devices is such a monolithic integrated circuit (Figure 8-8).

Some disadvantages of such circuits are its unipolar inputs and the variation of its bandwidth with the signal amplitude. The problem of bandwidth variation arises from the variation of emitter resistance, R_E, with current in the grounded-base transistor. With reference to Figure 8-13, R_E is inversely proportional to the emitter current, being approximately 26 Ω at 1 mA. The bandwidth of the circuit is inversely proportional to the product of $R_E C_C$ (C_C may be an external compensation capacitor or merely stray capacitance) and thus is proportional to the transistor current. Therefore, if the logarithmic converter works over a 120 dB dynamic range, its bandwidth will vary by 1 million:1, which can be inconvenient. For details, see Analog Devices (1987).

In addition to adopting other improved logarithmic conversion techniques, a popular technique used in commercial analog multiplier ICs is the Gilbert cell. There is a linear relationship between the collector current of a silicon junction transistor and its transconductance (gain) that is given by the following equation:

$$\frac{dI_c}{dV_{BE}} = \frac{q}{kT} I_c \tag{8.16}$$

where

I_c = collector current;

V_{BE} = base-emitter voltage;

q = electron charge (1.60219×10^{-19});

k = Boltzmann's constant (1.38062×10^{-23});

$q/kT = 1/(25.69 \text{ mV})$ at 25°C.

This relationship may be exploited to construct a multiplier with a long-tailed pair of silicon transistors (Analog Devices, 1987), as shown in Figure 8-14.

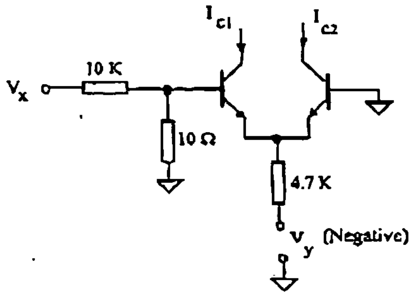


FIGURE 8-14 Basic transconductance multiplier circuit

At 25°C, this circuit provides an output of $q/kT[(V_y + V_{BE})/(4.7 \times 10^3)]$ $(10/10{,}010)V_x$ for the case of $I_{c1} - I_{c2} = \Delta I_c$.

However, this is a rather poor multiplier because

1. The y input is offset by the V_{BE}, which changes nonlinearly with V_y.
2. The x input is nonlinear as a result of the exponential relationship between I_c and V_{BE}.
3. The scale factor varies with temperature.

Gilbert realized that this circuit could be linearized and made temperature stable by working with currents rather than voltages and by exploiting the logarithmic properties of transistors, as per the case shown in Figure 8-15(a).

The x input to the Gilbert cell takes the form of a differential current, and the y input is a unipolar current. The differential x currents flow in two diode-connected transistors, and the logarithmic voltages compensate for the exponential V_{BE}/I_c relationship. Furthermore, the q/kT scale factors cancel each other. This gives the Gilbert cell the linear transfer function for $I_c = (I_{c1} - I_{c2})$:

$$\Delta I_c = \frac{\Delta I_x I_y}{I_x} \tag{8.17}$$

As it stands, the basic Gilbert cell shown in Figure 8-15(a) has three inconvenient features:

1. Its x input is a differential current.
2. Its output is a differential current.
3. Its y input is a unipolar current.

This makes the cell a two-quadrant multiplier.

By cross-coupling two such cells and using two voltage-to-current converters (as shown in Figure 8-15(b)), we can convert the basic architecture to a four-quadrant device with voltage inputs. A practical example of this type of a multiplier is the AD-534 from Analog Devices. In Figure 8-15(b), Q1A and Q1B

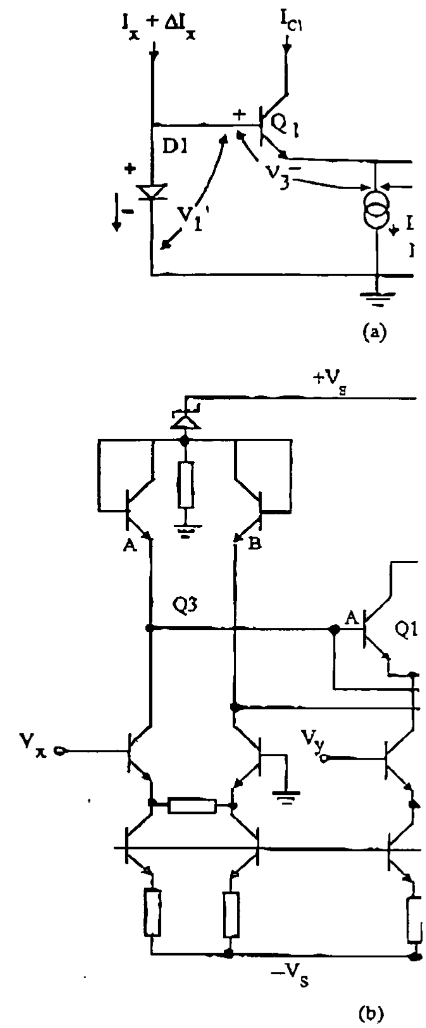
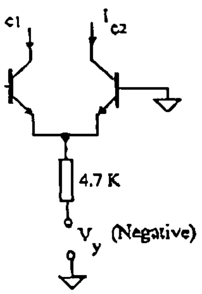


FIGURE 8-15 (a) Two-quadrant and (l
cell. (Reproduced by permission of Analog

and Q2A and Q2B form the two core l
while Q3A and Q3B are the linearizing
shows an operational amplifier acting
voltage converter; but for higher spee
tors of Q1 and Q2 form a differential



ultiplier circuit

put of $q/kT[(V_y + V_{BE})/(4.7 \times 10^3)]$
$= \Delta I_c$.
plier because

h changes nonlinearly with V_y.
the exponential relationship between I_c

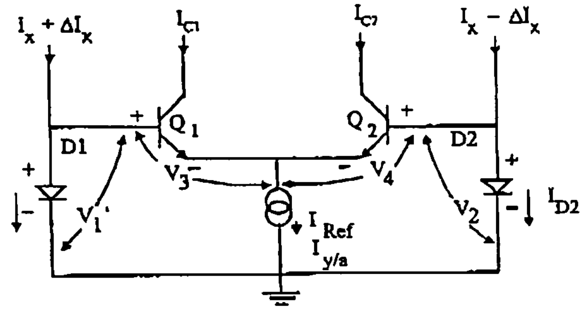
re.

ld be linearized and made temperature
in voltages and by exploiting the loga-
e case shown in Figure 8-15(a).
es the form of a differential current,
he differential x currents flow in two
arithmic voltages compensate for the
ore, the q/kT scale factors cancel each
r transfer function for $I_c = (I_{c1} - I_{c2})$:

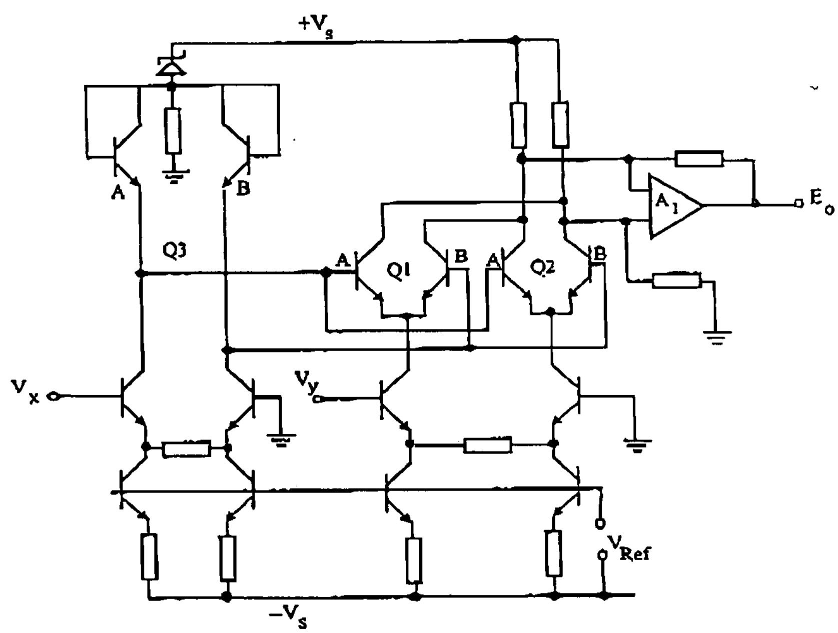
$$\frac{\Delta I_x I_y}{I_x} \qquad (8.17)$$

own in Figure 8-15(a) has three incon-

lier.
ising two voltage-to-current converters
vert the basic architecture to a four-
practical example of this type of a
ices. In Figure 8-15(b), Q1A and Q1B



(a)



(b)

FIGURE 8-15 (a) Two-quadrant and (b) four-quadrant multipliers based on Gilbert cell. (Reproduced by permission of Analog Devices, Inc.)

and Q2A and Q2B form the two core long-tailed pairs of the two Gilbert cells, while Q3A and Q3B are the linearizing transistors for both cells. Figure 8-15(b) shows an operational amplifier acting as a differential current to single-ended voltage converter, but for higher speed applications, the cross-coupled collectors of Q1 and Q2 form a differential open collector current output (as in the

AD-834 multiplier with a 500 MHz range). Motorola's MC 1494 and 1495 are other examples of four-quadrant multipliers.

A basic wideband multiplier using the AD-834 (for 500 MHz bandwidth) is shown in Figure 8-16(a). Figure 8-16(b) indicates the block diagram of a 10 MHz multiplier with direct-divide capability.

For details on multipliers, see Analog Devices (1995, Section 3).

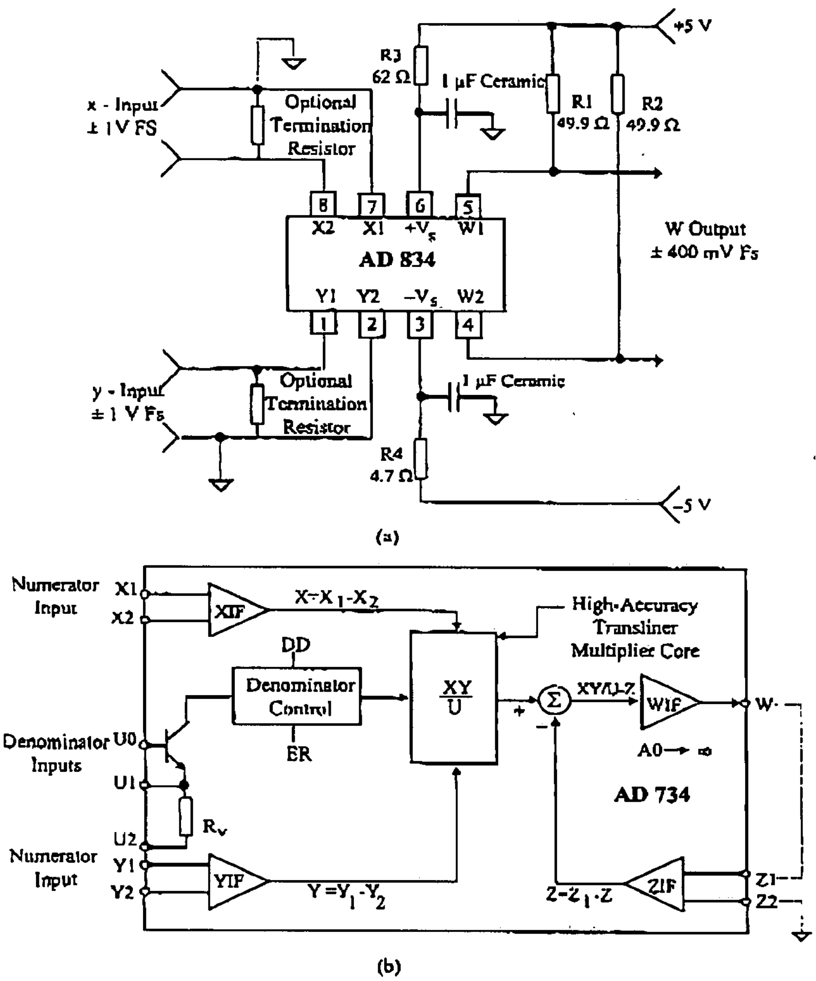


FIGURE 8-16 Practical multipliers: (a) A wideband application using the AD-834, (b) a 10 MHz multiplier with direct-divide capability using the AD-734. (Reproduced by permission of Analog Devices, Inc.)

8.6 RMS-to-DC Converters

The root mean square (RMS) is :
tude of an AC signal. Defined practi
signal is the amount of DC required
in the same load. Defined mathemati
value obtained by squaring the signal
square root. The averaging time must t
lowest frequencies of operation desire
converters can be found in Kitchen an
in multimeters are discussed in Kulara
in RMS-to-DC converters: explicit anc

8.6.1 Explicit Method

The explicit method is shown in
squared by a multiplier. The average va
and the square root is taken using an op
loop. This circuit has limited dynamic
squarer must try to deal with a signal t
restricts the method to inputs with a m
10:1 (20 dB). However, excellent ban
achieved with high accuracy if a mul
building block (see Figure 8-17(b)).

8.6.2 Implicit Method

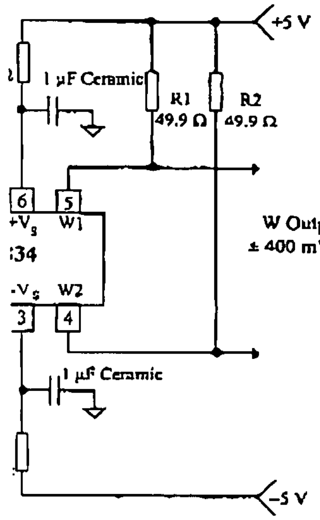
Figure 8-18 shows the circuit for
using the implicit method. Here, the ou
of a multiplier such as the AD-734. In
varies linearly (instead of as the square
considerably increases the dynamic ran
the explicit circuit. The disadvantage of
bandwidth than the explicit computation

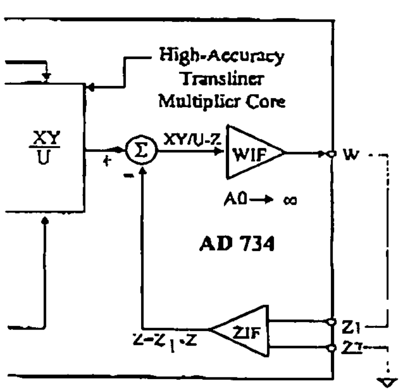
8.6.3 Monolithic RMS/DC Co

While it is possible to construct suc
far simpler to design a dedicated RMS ci
driven and only one quadrant if the inpu
circuit. Figure 8-19(a) shows a block di
converter such as the AD-536. It is subdi
value circuit (active rectifier), squarer/di
fier. The input voltage, V_{in}, which can b
current, I_{in}, by an absolute value circuit.
squarer/divider, which has the transfer fu

ıgc). Motorola's MC 1494 and 1495 are
iers.
the AD-834 (for 500 MHz bandwidth) is
indicates the block diagram of a 10 MHz

log Devices (1995, Section 3).





wideband application using the AD-834.
pability using the AD-734. (Reproduced by

8.6 RMS-to-DC Converters

The root mean square (RMS) is a fundamental measurement of the magnitude of an AC signal. Defined practically, the RMS value assigned to the AC signal is the amount of DC required to produce an equivalent amount of heat in the same load. Defined mathematically, the RMS value of a voltage is the value obtained by squaring the signal, taking the average, and then taking the square root. The averaging time must be sufficiently long to allow filtering at the lowest frequencies of operation desired. A complete discussion of RMS-to-DC converters can be found in Kitchen and Counts (1986) and application of these in multimeters are discussed in Kularatna (1996). Two basic techniques are used in RMS-to-DC converters: explicit and implicit.

8.6.1 Explicit Method

The explicit method is shown in Figure 8-17(a). The input signal is first squared by a multiplier. The average value is taken by using an appropriate filter, and the square root is taken using an op amp with a second squarer in the feedback loop. This circuit has limited dynamic range because the stages following the squarer must try to deal with a signal that varies enormously in amplitude. This restricts the method to inputs with a maximum dynamic range of approximately 10:1 (20 dB). However, excellent bandwidth (greater than 100 MHz) can be achieved with high accuracy if a multiplier such as the AD-834 is used as a building block (see Figure 8-17(b)).

8.6.2 Implicit Method

Figure 8-18 shows the circuit for computing the RMS value of a signal using the implicit method. Here, the output is fed back to the direct-divide input of a multiplier such as the AD-734. In this circuit, the output of the multiplier varies linearly (instead of as the square) with the RMS value of the input. This considerably increases the dynamic range of the implicit circuit as compared to the explicit circuit. The disadvantage of this approach is that it generally has less bandwidth than the explicit computation.

8.6.3 Monolithic RMS/DC Converters

While it is possible to construct such an RMS circuit from an AD-734, it is far simpler to design a dedicated RMS circuit. The V_{in}^2/V_z circuit may be current driven and only one quadrant if the input first passes through an absolute value circuit. Figure 8-19(a) shows a block diagram of a typical monolithic RMS/DC converter such as the AD-536. It is subdivided into four major sections: absolute value circuit (active rectifier), squarer/divider, current mirror, and buffer amplifier. The input voltage, V_{in}, which can be AC or DC, is converted to a unipolar current, I_{in}, by an absolute value circuit. I_{in} drives one input of the one-quadrant squarer/divider, which has the transfer function I_{in}^2/I_f. The output current, I_{in}^2/I_f,

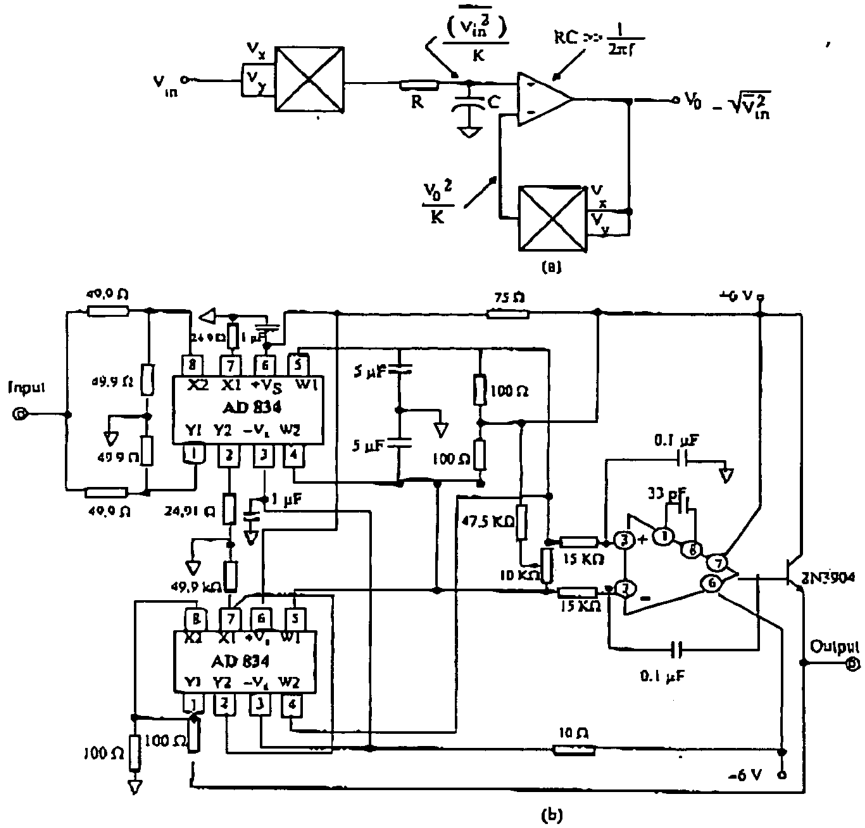


FIGURE 8-17 The explicit method of RMS-to-DC conversion: (a) basic technique, (b) wideband RMS measurement using the AD-834. (Reproduced by permission of Analog Devices, Inc.)

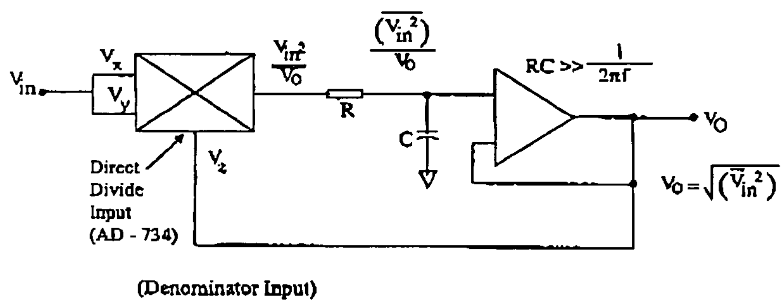


FIGURE 8-18 Implicit RMS computation

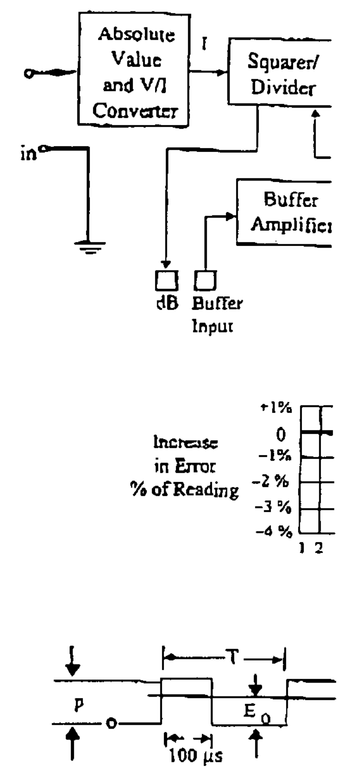
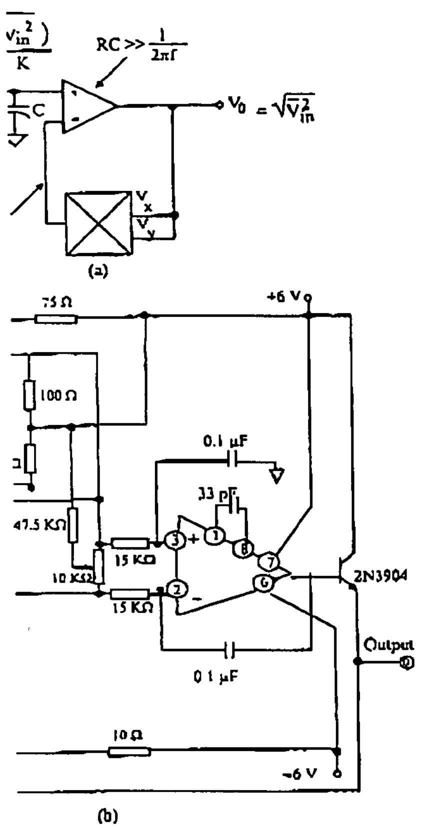


FIGURE 8-19 The AD-536 RMS/DC ... crest factor, (c) input waveform used for ... Devices, Inc.)

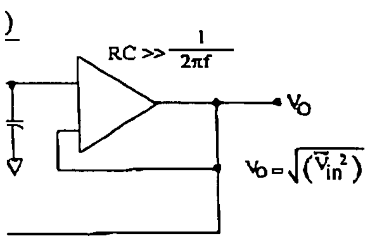
of the squarer/divider drives the curren... by R_1 and an externally connected capa... much greater than the longest period of ... averaged. The current mirror returns a ... of I_{in}^2/I_f back to the squarer/divider to ... Therefore,

$$I_f = \left(\frac{I_{in}^2}{I_f}\right)$$

The current mirror also produces th... The circuit provides a decibel output a... of approximately 3300 ppm/°C and mu...



IS-to-DC conversion: (a) basic technique,
334. (Reproduced by permission of Analog



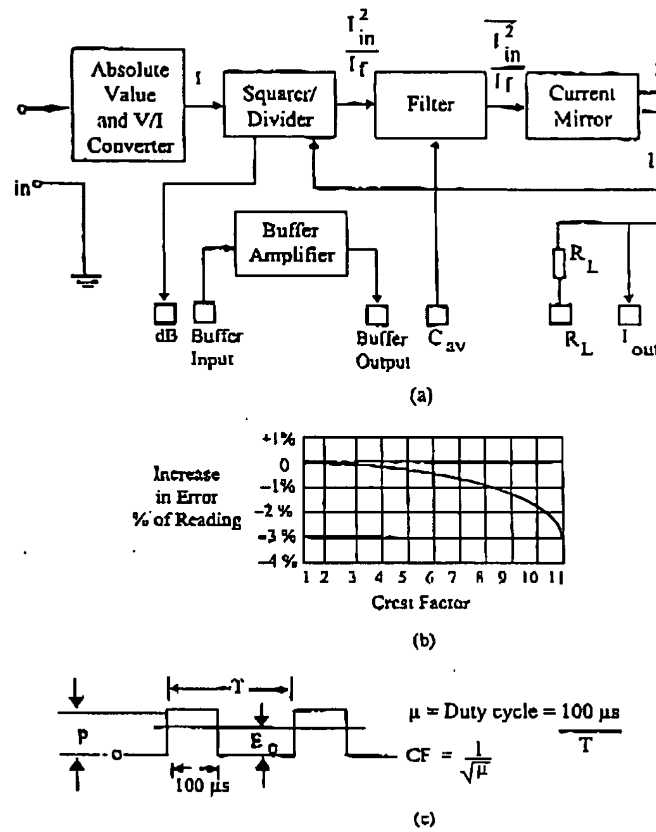


FIGURE 8-19 The AD-536 RMS/DC converter: (a) block diagram, (b) error against crest factor, (c) input waveform used for (b). (Reproduced by permission of Analog Devices, Inc.)

of the squarer/divider drives the current mirror through a low-pass filter formed by R_1 and an externally connected capacitor, C_{AV}. If the R_1C_{AV} time constant is much greater than the longest period of the input signal, then I_{in}^2/I_f is effectively averaged. The current mirror returns a current, I_f, that equals the average value of I_{in}^2/I_f back to the squarer/divider to complete the implicit RMS computation. Therefore,

$$I_f = \left(\frac{I_{in}^2}{I_f}\right) = I_{in}(\text{RMS}) \tag{8.18}$$

The current mirror also produces the output current, I_{out}, which equals $2I_f$. The circuit provides a decibel output also, which has a temperature coefficient of approximately 3300 ppm/°C and must be temperature compensated.

TABLE 8-3 A representative set of RMS/DC converters from Analog Devices, Inc.

Part No.	*Bandwidth*	*Full-Scale Input Voltage Range*	*Remarks*
AD-536	450 kHz	>100 mV input	±15 V rails
	2 MHz	>1 V	
AD-636	1 MHz	Up to 200 mV	Low-power (±5 V) rails
	8 MHz		
AD-637	8 MHz	>1 V	Chip select/power down function available (±3 to ±18 V rails)
	600 kHz	200 mV	
AD-736	350 kHz	100 mV	Low-power precision converter
	460 kHz	200 mV	±5 to ±16 V power rails
AD-737	170 to 350 kHz	100 mV	Low-cost, low-power true RMS
	190 to 460 kHz	200 mV	±5 to ±16 V rails

There are a number of RMS/DC converters in monolithic form. A representative list from Analog Devices is shown in Table 8-3. For practical applications, design details, and selection of RMS/DC converters, see Analog Devices (1992c, 1995), Kitchen and Counts (1986), and Kularatna (1996).

8.7 Function Generators

Some interesting applications of nonlinear devices involve function generation using AD-538-type devices and AD-639 trigonometric function generators. To fully appreciate these devices, keep in mind that some digital techniques such as direct digital synthesis (DDS) still have restrictions at high frequencies, beyond several megahertz. An example of these could be shown using the AD-538. The arc-tangent circuit shown in Figure 8-20(a) is typical of AD-538 applications where Y is 1 so that $V_o = (Z/X)^M$ for $M < 1$.

In an approximation to the arc-tangent function, the AD-538 may be made to compute the angle represented by two rectangular coordinates, which, since they are applied to the X and Z inputs, we shall call X and Z rather than the more usual X and Y. If X and Z are within the range 100 µV to 10 V, the error in the computed angle is under 1° (the AD-639 can perform a similar computation with fewer components but cannot work over a wide dynamic range).

The circuit exploits the fact that

$$T = \frac{(\tan T)^{1.21}}{1 + (\tan T)^{1.21}} \tag{8.19}$$

where T is the angle normalized to 90°.

The AD-538 and the external amplifier calculate log(tan T) from X and Z, amplifie it by a factor of 1.21 to raise to the 1.21 power, and perform an implicit calculation to calculate the angle (which is expressed in terms of the

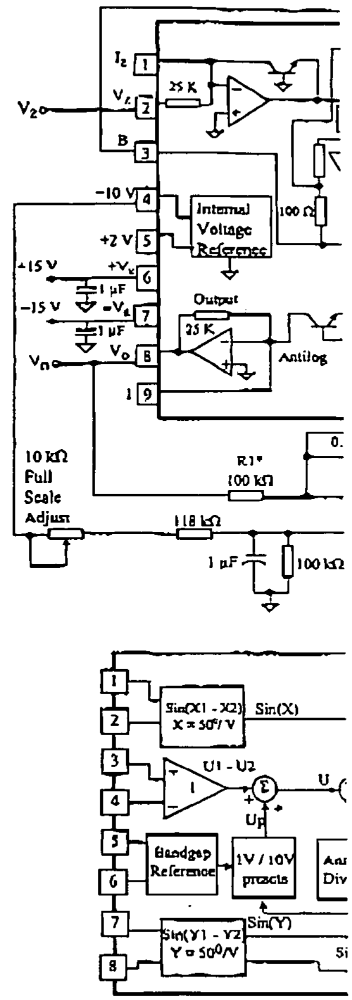


FIGURE 8-20 Nonlinear devices us
tion using the AD-538, (b) the AD-639
(Reproduced by permission of Analog D

reference voltage). Under these cond
the angle tends to 90° although, in f
89.5° because at 90° tangents become
unstable. R_1 and R_2 must be match
stabilized by the 0.1 µF integrating c
circuit works in a single quadrant sir

)C converters from Analog Devices, Inc.

ale Input e Range	Remarks
nV input	±15 V rails
00 mV	Low-power (±5 V) rails
	Chip select/power down function available (±3 to ±18 V rails)
V	
V	Low-power precision converter
V	±5 to ±16 V power rails
V	Low-cost, low-power true RMS
V	±5 to ±16 V rails

verters in monolithic form. A represen-
n Table 8-3. For practical applications,
converters, see Analog Devices (1992c,
ularatna (1996).

linear devices involve function genera-
639 trigonometric function generators.
mind that some digital techniques such
restrictions at high frequencies, beyond
ould be shown using the AD-538. The
(a) is typical of AD-538 applications
< 1.
nt function, the AD-538 may be made
rectangular coordinates, which, since
shall call X and Z rather than the more
ic range 100 μV to 10 V, the error in
539 can perform a similar computation
over a wide dynamic range).

$$\frac{T)^{1.21}}{\mathrm{an}\, T)^{1.21}} \qquad (8.19)$$

lifier calculate log(tan T) from X and
se to the 1.21 power, and perform an
e (which is expressed in terms of the

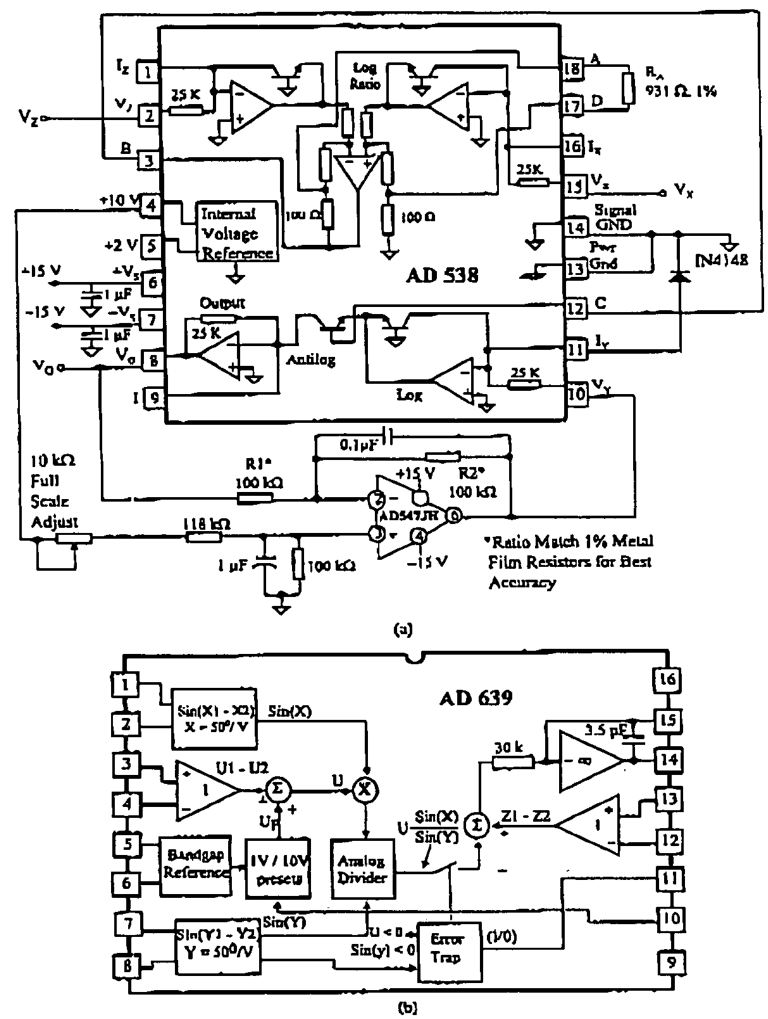


FIGURE 8-20 Nonlinear devices used as function generators: (a) arc-tangent function using the AD-538, (b) the AD-639, a universal trigonometric function generator. (Reproduced by permission of Analog Devices, Inc.)

reference voltage). Under these conditions, the output voltage tends to V_{REF} as the angle tends to 90° although, in fact, the circuit cannot be used much above 89.5° because at 90° tangents become infinite and before that the circuit becomes unstable. R_1 and R_2 must be matched for highest accuracy, and the circuit is stabilized by the 0.1 μF integrating capacitor in the amplifier feedback path. The circuit works in a single quadrant since both X and Z must be positive.

Trigonometric functions more normally are calculated by the AD-639. No external components (other than supply decoupling capacitors) are required to compute sines, cosines, tangents and cotangents, and secants and cosecants with the AD-639. Little more than an extra reference voltage (which may be generated from the internal reference with an operational amplifier and a couple of resistors) is required for versines and coversines. For details of the less common functions, consult the AD-639 data sheet (Analog Devices, 1999) and various application notes—the sine, cosine, and tangent will be described here. Some interesting applications of the AD-639 are discussed in Analog Devices (1987).

8.8 Benistor, a Newly Introduced Device

An interesting novel component surfaced recently (Bindra, 1998) from the Bensys Corporation, the Benistor™. (The name Benistor is a combination of the company's name and transistor.) The Benistor, which performs similar to multielectrode vacuum tubes, can independently control the voltage and current output from the device.

Introduced in 1998, the device block diagram, shown in Figure 8-21(a), comprises four blocks: the power controller (PC), the current separator (CS), the current controller (CC), and the voltage threshold controller (VTC). In the first commercial device, BEN 35100, the PC is a simple PNP transistor that acts as a switch or a variable resistor between the power source and the load. The CS block incorporates three NPN transistors to enable the voltage controller and current controller to work simultaneously or separately.

Comprising two open-collector op amps and two resistors, the current controller acts as a voltage/current converter for the power controller. There are two control inputs to this block: the noninverting input CC and the inverting input $\overline{CC}$. The amount of voltage input at the noninverting current control is directly proportional to the current output to the load, and the amount of voltage at the inverting electrode is inversely proportional to the output current. Functioning as a window comparator, the VTC controls the buffer's base current, in either a switching or self-switching mode. The two controls of the VTC are effective voltage control (EVC) and maximum voltage control (MVC), which determine the threshold voltages of the output. While the voltage at the EVC establishes the threshold for switching from off to on, the voltage at MVC pin determines the on/off states. In effect, the voltage settings on these two pins pre-establish the output voltage window.

In summary, the Benistor is a multielectrode device consisting of impedance command pins for precise control of output current and voltage. Consequently, eight electrodes completely define the Benistor. These are shown in Figure 8-21(b).

The SS electrode (not used in the BEN 35100 version) sets the initial state of the Benistor's self-switching mode of operation as either on or off at the beginning of an input power pulse wave. Having only two states, it is either grounded (on) or floating (off). Likewise, the CE provides the reference voltage

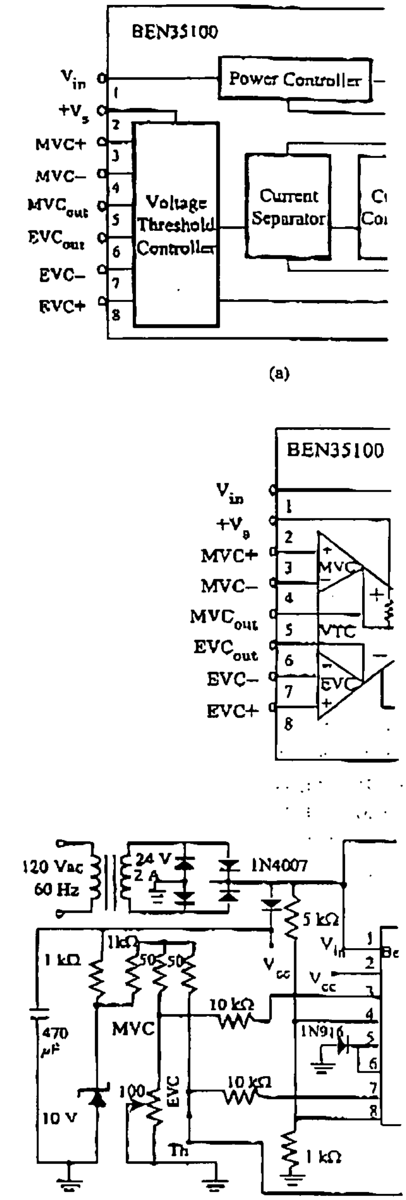


FIGURE 8-21 The Benistor: (a) bloc
lent circuit, (d) a soldering iron applicatio
by permission of the Bensys Corporation.

ly are calculated by the AD-639. No
:coupling capacitors) are required to
gents, and secants and cosecants with
:nce voltage (which may be generated
nal amplifier and a couple of resistors)
details of the less common functions,
:vices, 1999) and various application
be described here. Some interesting
n Analog Devices (1987).

:ed Device

.ced recently (Bindra, 1998) from the
: name Benistor is a combination of
Benistor, which performs similar to
lently control the voltage and current

< diagram, shown in Figure 8-21(a),
ler (PC), the current separator (CS),
ge threshold controller (VTC). In the
C is a simple PNP transistor that acts
the power source and the load. The
:s to enable the voltage controller and
or separately.
ps and two resistors, the current con-
for the power controller. There are
.nverting input CC and the inverting
it the noninverting current control is
o the load, and the amount of voltage
portional to the output current. Func-
C controls the buffer's base current,
de. The two controls of the VTC are
.mum voltage control (MVC), which
utput. While the voltage at the EVC
m off to on, the voltage at MVC pin
: voltage settings on these two pins

ctrode device consisting of impedance
it current and voltage. Consequently,
tor. These are shown in Figure 8-21(b).
N 35100 version) sets the initial state
operation as either on or off at the
Having only two states, it is either
the CE provides the reference voltage

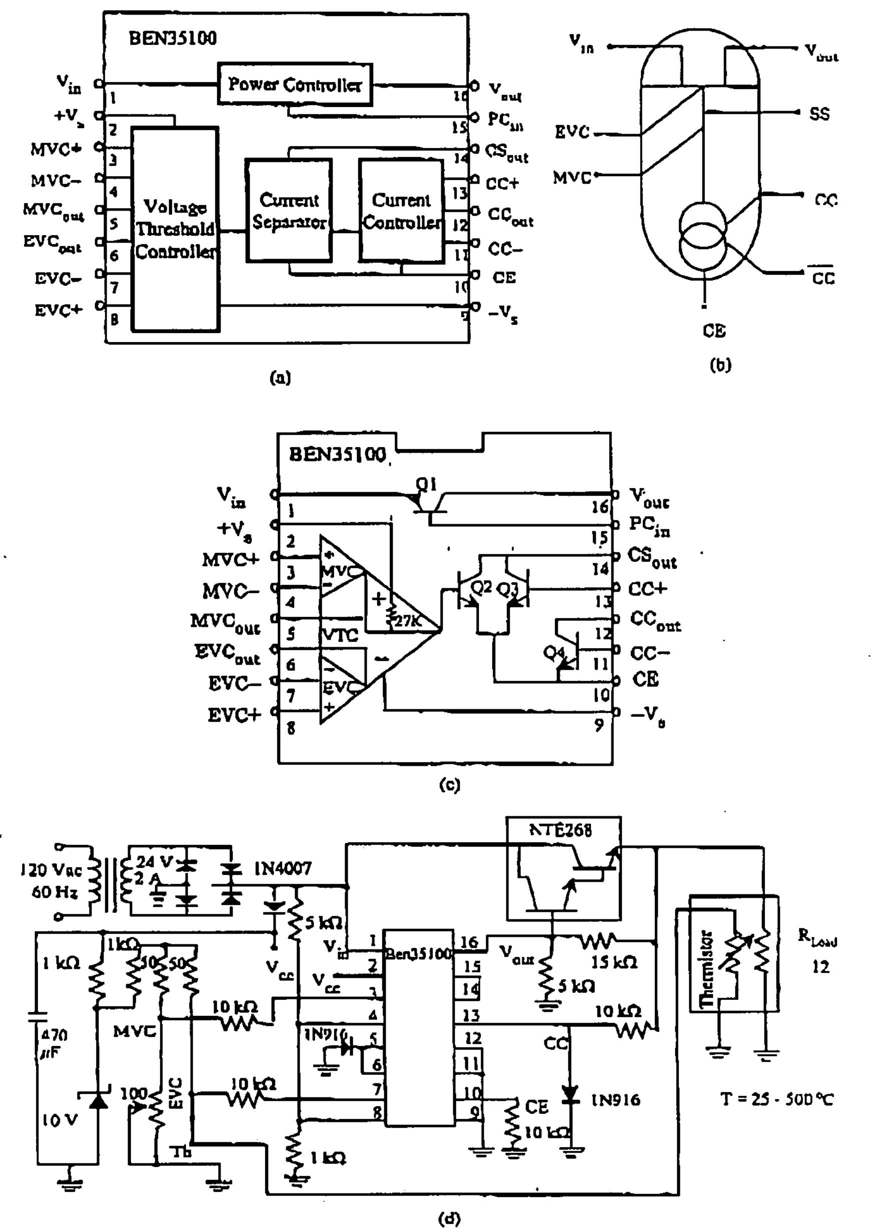


FIGURE 8-21 The Benistor: (a) block diagram, (b) symbol, (c) BEN 35100 equivalent circuit, (d) a soldering iron application for precise temperature control. (Reproduced by permission of the Bensys Corporation.)

for the device, while the CC determines the window of output current, and the VTC pre-establishes the window of output voltage. Based on these settings, the power controller will deliver to the load only that part of the input power signal, with respect to the amount of current and voltage, within the two pre-established ranges. In effect, together, the voltage and current-control electrodes can provide the system designer virtually any output possibility.

Because the device can accept AC, DC, and pulse input and provide output in any of these modes or any combination (based on conditions at the control electrodes), the Benistor inspires a new way of thinking in power control and power conversion. Combining the capability of all three previous values, it provides designers a unique method of controlling power parameters. Figure 8-22 indicates

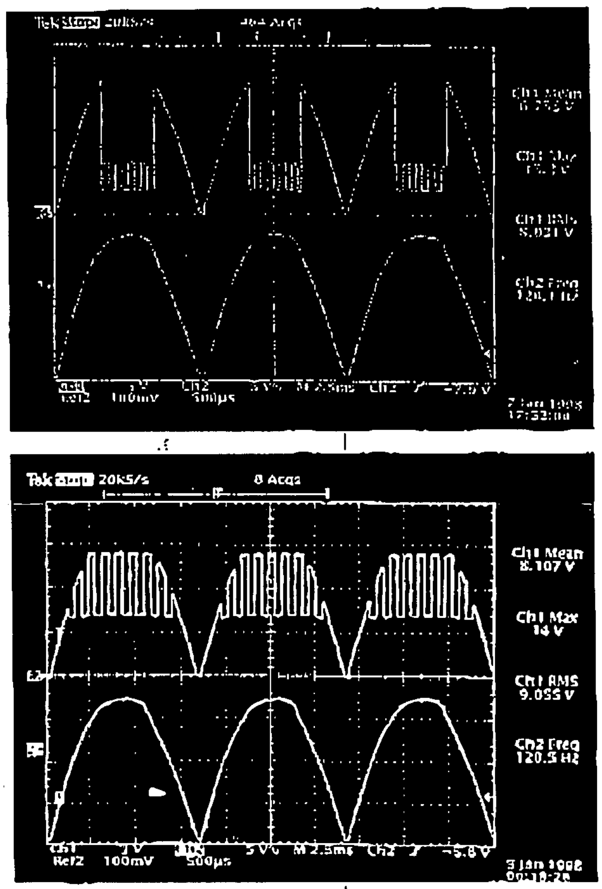


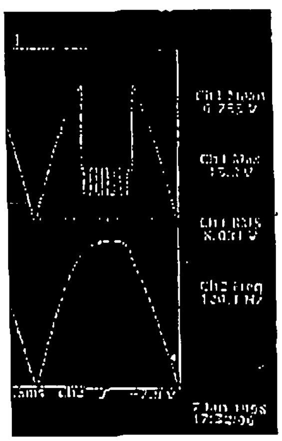
FIGURE 8-22. Waveform control example. (Reproduced by permission of Bensys Corporation.)

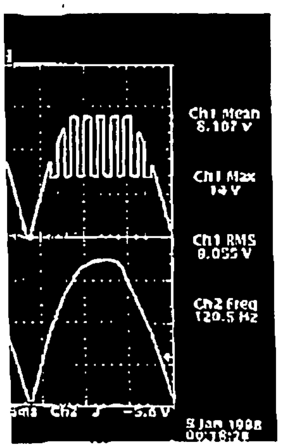
complex waveforms that can be obtai
For further details, see Bindra (1998),
•••) and U.S. Patent No. 5,598,093.

References

Analog Devices. Linear Design Seminar. Analo
Analog Devices. High Speed Design Seminar. /
Analog Devices. *Amplifier Applications Guide.*
Analog Devices. *High Speed Design Techniques.*
Analog Devices. "AD640: DC Coupled Demodu *Linear Reference Manual*, rev. A. Analog Dev 3-46.
Analog Devices. Linear Design Seminar. Analo
Analog Devices. "AD639—Universal Trigono Devices, Inc. (Norwood, MA, USA), Designe
Bensys Corporation. "Preliminary Data Sheet, I USA September 11, 1998.
Bensys Corporation. "Incandescent Lamp Flash vale, CA, USA •••.
Bensys Corporation. "DC to DC Converters." Ap USA •••.
Bensys Corporation. "Lithium Ion Battery Charg vale, CA, USA •••.
Bensys Corporation. *User Manual—EB 16 Evalu* USA •••.
US Patent Number 5,598,093, January 28, 1997: Controlling Energy Delivered to a Load and M
Bindra, Ashok. "Unique Valve Independently Con 1998), pp. 35–40.
Gilbert, Barrie. *ISSCC Digest of Technical Paper*
Gilbert, Barrie. *Journal of Solid State Circuits* SC
Hughes, Richard Smith. *Logarithmic Amplifiers.*
Kitchen, Charles, and Lew Counts. *RMS to DC* Devices, Inc., 1986.
Kularatna, N. *Modern Electronic Test and Measur*
Sheingold, Daniel H. *Nonlinear Circuits Handboo*

the window of output current, and the
ıt voltage. Based on these settings, the
nly that part of the input power signal,
voltage, within the two pre-established
current-control electrodes can provide
ɔossibility.
)C, and pulse input and provide output
based on conditions at the control elec-
ıf thinking in power control and power
all three previous values, it provides
ower parameters. Figure 8-22 indicates





e. (Reproduced by permission of Bensys

complex waveforms that can be obtained from the same input (bottom traces). For further details, see Bindra (1998), and Bensys Corporation (•••, •••, •••, •••) and U.S. Patent No. 5,598,093.

References

Analog Devices. Linear Design Seminar. Analog Devices, Inc., 1987.
Analog Devices. High Speed Design Seminar. Analog Devices, Inc., 1990.
Analog Devices. *Amplifier Applications Guide*. Analog Devices, Inc. (Norwood, MA, USA) 1992a.
Analog Devices. *High Speed Design Techniques*. Analog Devices, Inc. (Norwood, MA, USA) 1992b.
Analog Devices. "AD640: DC Coupled Demodulating 120 MHz Logarithmic Amplifier." In *Special Linear Reference Manual*, rev. A. Analog Devices, Inc. (Norwood, MA, USA) 1992c, pp. 3-31 to 3-46.
Analog Devices. Linear Design Seminar. Analog Devices, Inc. (Norwood, MA, USA) 1995.
Analog Devices. "AD639—Universal Trigonometric Function Converter—Data Sheet." Analog Devices, Inc. (Norwood, MA, USA), Designer's Reference Manual (CD ROM), 1999.
Bensys Corporation. "Preliminary Data Sheet, BEN 35100." Bensys Corporation, Sunnyvale, CA, USA September 11, 1998.
Bensys Corporation. "Incandescent Lamp Flasher." Application note. Bensys Corporation, Sunnyvale, CA, USA •••.
Bensys Corporation. "DC to DC Converters." Application note. Bensys Corporation, Sunnyvale, CA, USA •••.
Bensys Corporation. "Lithium Ion Battery Charger." Application note. Bensys Corporation, Sunnyvale, CA, USA •••.
Bensys Corporation. *User Manual—EB 16 Evaluation Board*. Bensys Corporation, Sunnyvale, CA, USA •••.
US Patent Number 5,598,093, January 28, 1997: "Low Dissipation Controllable Electron Value for Controlling Energy Delivered to a Load and Method Therefor."
Bindra, Ashok. "Unique Valve Independently Controls Power Parameters." *Electronic Design* (July 6, 1998), pp. 35–40.
Gilbert, Barrie. *ISSCC Digest of Technical Papers* (February 16, 1968), pp. 114–115.
Gilbert, Barrie. *Journal of Solid State Circuits* SC-3 (December 1968), pp. 353–372.
Hughes, Richard Smith. *Logarithmic Amplifiers*. Dedham, MA: Artech House. 1986.
Kitchen, Charles, and Lew Counts. *RMS to DC Conversion Application Guide*, 2nd ed. Analog Devices, Inc., 1986.
Kularatna, N. *Modern Electronic Test and Measuring Instruments*. London: IEEE, 1996.
Sheingold, Daniel H. *Nonlinear Circuits Handbook*. Analog Devices, Inc., 1976.

CHAPTER 9

Rechargeable Batteries and Their Management

9.1 Introduction

The insatiable demand for smaller, lightweight portable electronic equipment has dramatically increased the need for research on rechargeable (or secondary) battery chemistries. In addition to achieving improved performance on lead acid and nickel cadmium (NiCd) batteries, during the last decade, many new chemistries such as nickel metal hydride (NiMH), lithium ion (Li-ion), rechargeable alkaline, silver-zinc, zinc-air, lithium polymer, and the like have been introduced.

Higher energy density, superior cycle life, environmental friendliness, and safe operation are among the general design targets of battery manufacturers. To complement these developments many semiconductor manufacturers have introduced new integrated circuit families to achieve the best charge/discharge performance and longest possible lifetime from battery packs.

This chapter describes the characteristics of battery families such as sealed lead acid, NiCd, NiMH, Li-ion, rechargeable alkaline, and zinc-air together with modern techniques used in battery management ICs, without elaborating on the battery chemistries. Concepts and applications related to systems management bus and smart battery system also are introduced.

9.2 Battery Terminology

9.2.1 Capacity

Battery or cell capacity is measured as an integral of current (i) over a defined period of time (t):

$$\text{Capacity} = \int_0^t i\,dt$$

This equation applies to either the charge or discharge; that is, the capacity added or capacity removed from a battery or cell. The capacity of a battery or cell is measured in milliampere-hours (mAh) or ampere-hours (Ah).

Although the basic definition is simple, many different forms of capacity are used in the battery industry. The distinctions among them reflect differences in the conditions under which the capacity is measured.

Standard capacity measures the total capacity that a relatively new but stabilized production cell or battery can store and discharge under a defined standard set of application conditions. It assumes that the cell or battery is fully formed, charged at the standard temperature at the specification rate, and discharged at the same standard temperature at a specified standard discharge rate to a standard end-of-discharge voltage (EODV). The standard EODV itself is subject to variation depending on discharge rate as discussed.

When any of the application conditions differ from standard, the capacity of the cell or battery changes. The term **actual capacity** includes all nonstandard conditions that alter the amount of capacity the fully charged new cell or battery is capable of delivering when fully discharged to a standard EODV. Examples of such situations might include subjecting the cell or battery to a cold discharge or a high-rate discharge.

That portion of actual capacity which can be delivered by the fully charged new cell or battery to some nonstandard EODV is called **available capacity**. Therefore, if the standard EODV is 1.6 volts per cell, the available capacity to an EODV of 1.8 volts per cell would be less than the actual capacity.

Rated capacity is the minimum expected capacity when a new but fully formed cell is measured under standard conditions. This is the basis for C rate and depends on the standard conditions used, which may vary depending on the manufacturers and the battery types.

If a battery is stored for a period of time following a full charge, some of its charge will dissipate. The capacity that remains and can be discharged is called the **retained capacity**.

9.2.2 C Rate

The C rate is the rate in amperes or milliamperes numerically equal to the capacity rating of the cell given in ampere-hours or milliampere-hours. For example, a cell with a 1.2 Ah capacity has a C rate of 1.2 amps. The C concept simplifies the discussion of charging for a broad range of cell sizes, since the cells' responses to charging are similar if the C rate is the same. Normally, a 4 Ah cell will respond to a 0.4 amp (0.1 C) charge rate in the same manner that a 1.4 Ah cell will respond to a 0.14 amp (also 0.1 C) charge rate.

The rate at which current is drawn from a battery affects the amount of energy that can be obtained. At low discharge rates the actual capacity of a battery is greater than at high discharge rates. This relationship is shown in Figure 9-1.

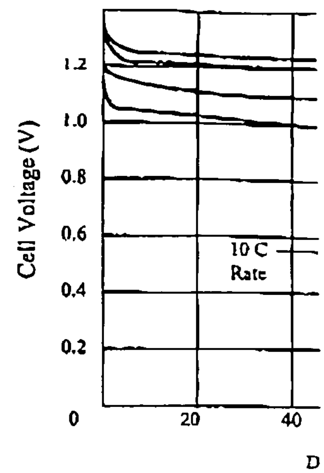


FIGURE 9-1 Capacity vs. discharge r

9.2.3 Energy Density

The energy density of a cell is its
This is called the **gravimetric energ**
volumetric energy density when vol
and **specific energy** sometimes are usec
respectively; Bennett and Brown, 1997

9.2.4 Cycle Life

Cycle life is a measure of a batt
discharging and recharging using the m
dations and still provide the minimu
Cyclic discharge testing can be done
discharge to simulate conditions in the
ever, that cycle life has an inverse loga

9.2.5 Cyclic Energy Density

For comparison, a better measur
is a composite characteristic that co
life of the battery. This composite ch
product of energy density and cycle l
in the dimensional units watt-hour-cyc
cycles/liter (volumetric).

ɪrge or discharge; that is, the capacity
or cell. The capacity of a battery or
h) or ampere-hours (Ah).
le, many different forms of capacity
ctions among them reflect differences
is measured.
ıl capacity that a relatively new but
store and discharge under a defined
assumes that the cell or battery is
perature at the specification rate, and
ıre at a specified standard discharge
(EODV). The standard EODV itself
rge rate as discussed.
s differ from standard, the capacity of
ıal **capacity** includes all nonstandard
the fully charged new cell or battery
rged to a standard EODV. Examples
the cell or battery to a cold discharge

can be delivered by the fully charged
EODV is called **available capacity**.
ılts per cell, the available capacity to
ss than the actual capacity.
ected capacity when a new but fully
nditions. This is the basis for C rate
d, which may vary depending on the

ıe following a full charge, some of its
nains and can be discharged is called

r milliamperes numerically equal to
pere-hours or milliampere-hours. For
a C rate of 1.2 amps. The C concept
broad range of cell sizes, since the
the C rate is the same. Normally, a
) charge rate in the same manner that
also 0.1 C) charge rate.
rom a battery affects the amount of
harge rates the actual capacity of a
rates. This relationship is shown in

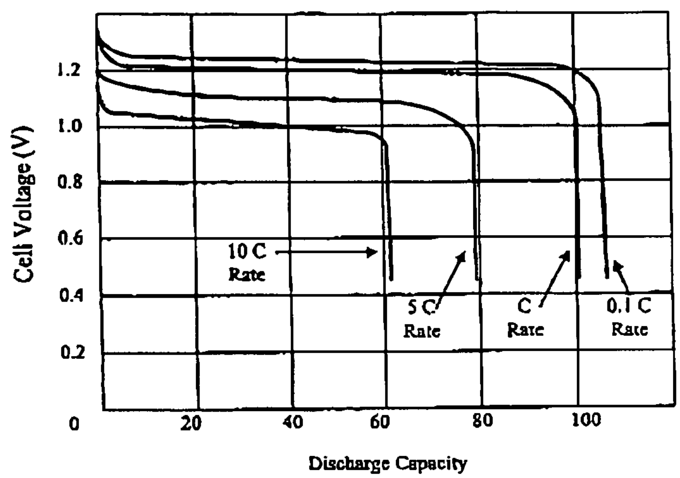


FIGURE 9-1 Capacity vs. discharge rate of a typical cell

9.2.3 Energy Density

The energy density of a cell is its energy divided by its weight or volume. This is called the **gravimetric energy density** when weight is used, and the **volumetric energy density** when volume is used. (The terms **energy density** and **specific energy** sometimes are used for volumetric and gravimetric measures, respectively; Bennett and Brown, 1997.)

9.2.4 Cycle Life

Cycle life is a measure of a battery's ability to withstand repetitive deep discharging and recharging using the manufacturer's cyclic charging recommendations and still provide the minimum required capacity for the application. Cyclic discharge testing can be done at any of various rates and depths of discharge to simulate conditions in the application. It must be recognized, however, that cycle life has an inverse logarithmic relationship to depth of discharge.

9.2.5 Cyclic Energy Density

For comparison, a better measure of rechargeable battery characteristics is a composite characteristic that considers energy density over the service life of the battery. This composite characteristic, cyclic energy density, is the product of energy density and cycle life at that energy density and measured in the dimensional units watt-hour-cycles/kilogram (gravimetric) or watt-hour-cycles/liter (volumetric).

9.2.6 Self-Discharge Rate

The self-discharge rate is a measure of how long a battery can be stored and still provide the minimum required capacity and be rechargeable to the rated capacity. This commonly is measured by placing batteries on shelf at room (or elevated) temperature and monitoring open circuit voltage over time. Samples are discharged at periodic intervals to determine remaining capacity and recharged to determine rechargeability.

9.2.7 Charge Acceptance

Charge acceptance is the willingness of a battery or cell to accept a charge. This is affected by cell temperature, charge rate, and the state of charge.

9.2.8 Depth of Discharge

The depth of discharge is the capacity removed from a battery divided by its actual capacity, expressed as a percentage.

9.2.9 Voltage Plateau

The voltage plateau is the protracted period of very slowly declining voltage that extends from the initial voltage drop at the start of a discharge to the knee of the discharge curve (Figure 9-2).

9.2.10 Midpoint Voltage

The midpoint voltage is the battery voltage when 50% of the actual capacity has been delivered (see Figure 9-2).

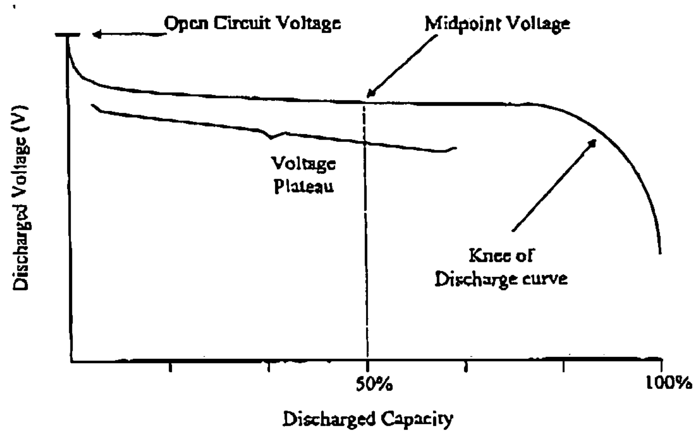


FIGURE 9-2 Nominal discharge performance for sealed lead-acid cells

9.2.11 Overcharge

Overcharge is the continued c charged. When a cell is not yet fully current is converted to chemical ene when all the available active materi energy available in the charging cur to activate other nonuseful chemical

9.3 Battery Technology: /

Many types of rechargeable che most batteries are NiCd, NiMH, anc headway into portable systems. The for a given system is typically lim A comparison of some basic charac chemistry is depicted in Table 9-1.

NiCd batteries presently power r technology is mature and well under increasing regulatory scrutiny (inclu tions) and the maturity of NiCd tech life cycle improvements already have

NiMH offers incremental impro and volume over NiCd. Li-ion is bette and per kilogram of NiCd batteries. A a higher price. NiMH and Li-ion are in in applications that support a higher NiMH and Li-ion chemistry, howeve

TABLE 9-1 Battery chemistry charac

Parameter	*Units/Conditions*	*Sealed Lead Acid*
Cell voltage	Volts	2.0
Relative cost	NiCd = 1	0.6
Self-discharge	%/month	2–4%
Cycle life	Cycles to reach 80% of rated capacity	500–2000
Overcharge tolerance	—	High
Energy by volume	Watt hour/liter	70–110
Energy by weight	Watt hour/kg	30–45

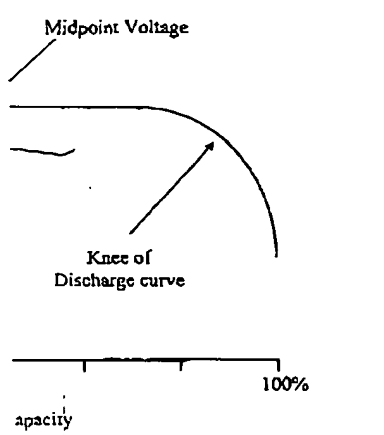
›f how long a battery can be stored ıcity and be rechargeable to the rated lacing batteries on shelf at room (or :ircuit voltage over time. Samples are ıe remaining capacity and recharged

f a battery or cell to accept a charge. rate, and the state of charge.

removed from a battery divided by ;e.

riod of very slowly declining voltage t the start of a discharge to the knee

:age when 50% of the actual capacity



e for sealed lead-acid cells

9.2.11 Overcharge

Overcharge is the continued charging of a cell after it has become fully charged. When a cell is not yet fully charged, the electrical energy of the charge current is converted to chemical energy in the cell by the charging reactions. But, when all the available active material has been converted to a charged state, the energy available in the charging current goes to produce gases from the cell or to activate other nonuseful chemical reactions.

9.3 Battery Technology: An Overview

Many types of rechargeable chemistry are used in electronic systems. Today, most batteries are NiCd, NiMH, and sealed lead acid, with lithium-ion making headway into portable systems. The choice of a particular battery technology for a given system is typically limited by size, weight, cycle life, and cost. A comparison of some basic characteristics of the five major types of battery chemistry is depicted in Table 9-1.

NiCd batteries presently power most rechargeable consumer appliances. The technology is mature and well understood. However, cadmium is coming under increasing regulatory scrutiny (including mandatory recycling in some jurisdictions) and the maturity of NiCd technology also means most of the capacity and life cycle improvements already have been made.

NiMH offers incremental improvements in energy density both by weight and volume over NiCd. Li-ion is better still, offering over twice the watts per liter and per kilogram of NiCd batteries. As always, this higher performance comes at a higher price. NiMH and Li-ion are increasing in popularity as upgrade options or in applications that support a higher price/performance point. The advantages of NiMH and Li-ion chemistry, however, also come at the cost of greater electrical

TABLE 9-1 Battery chemistry characteristics

Parameter	*Units/Conditions*	*Sealed Lead Acid*	*NiCd*	*NiMH*	*Li-ion*	*Rechargeable Alkaline*
Cell voltage	Volts	2.0	1.2	1.2	3.6	1.5
Relative cost	NiCd = 1	0.6	1	1.6	2	0.5
Self-discharge	%/month	2–4%	15–30%	18–20%	6–10%	0.3%
Cycle life	Cycles to reach 80% of rated capacity	500–2000	500–1000	500–800	1000–1200	<25
Overcharge tolerance	—	High	Medium	Low	Very low	Medium
Energy by volume	Watt hour/liter	70–110	120–150	250–300	280–320	220
Energy by weight	Watt hour/kg	30–45	40–50	70–80	110–130	80

fragility. Li-ion particularly is more easily and extensively damaged by less than optimal battery management, so much so that fail-safe circuits to disconnect the cells from the load under overcurrent or overtemperature conditions usually are built into the battery pack.

Rechargeable alkaline batteries mimic the form and replace the function of disposable household batteries. While initially more expensive, they cost less over their lifetime than the equivalent in disposable batteries. They are the least expensive form of rechargeable chemistry for low current applications and have the lowest self-discharge rate. However, they have the shortest cycle life in deep discharge applications.

Lead-acid batteries are most familiar in automobiles because they are the most economical chemistry for delivering large currents. Lead-acid batteries also have a long trickle life and therefore serve well for classic "floating" applications. Although flooded lead-acid technology is popular for automobile and similar applications, sealed lead-acid batteries serve the electronic engineering environment. On the downside, lead-acid has the least capacity by volume and weight.

Table 9-1 lists the major advantages and disadvantages of the five chemistries. Chemistry selection involves trade-offs driven by the technical requirements and economics of the application.

9.4 Lead-Acid Batteries

9.4.1 *Flooded Lead-Acid Batteries*

The flooded lead-acid battery of today basically uses the design developed by Faure in 1881. It consists of a container with multiple plates immersed in a pool of dilute sulfuric acid. Recombination is minimal, so water is consumed throughout the battery life and the batteries can emit corrosive and explosive gases when experiencing overcharge. So-called maintenance-free forms of flooded batteries provide excess electrolytes to accommodate water loss throughout a normal life cycle. Most industrial applications for flooded batteries are found in motive power, engine starting, and large system power backup. Today, other forms of battery have largely supplanted flooded batteries in small- and medium-capacity applications, but in larger sizes flooded lead-acid batteries continue to dominate. By far, the biggest application for flooded batteries is starting, lighting, and ignition service on automobiles and trucks. Large flooded lead-acid batteries also provide motive power for equipment ranging from forklifts to submarines and provide emergency power backup for many electrical applications, most notably the telecommunication network.

9.4.2 *Sealed Lead-Acid Batteries*

Sealed lead-acid batteries first appeared in commercial use in the early 1970s. Although the governing reactions of the sealed cell are the same as other

forms of lead-acid batteries, the key
occurs in the sealed cell as it reache
acid systems, the excess energy frc
of water in the electrolyte with the
because the excess electrolyte prevei
plate and possibly recombining. Thu
must be replenished. The sealed-lea
uses recombination to reduce or elim

Sealed lead-acid batteries for ele
from the type commonly found in th
lead-acid batteries: the original gell
system. The gelled electrolyte syste
an electrolyte, causing it to set up in
a fine glass fiber separator to absorl
the retained system is called an absc
known as a *starved design*. *Starved*
separator create a limitation to the
ties of the separator. In certain case
trayed in a specific position for opti
AGM, are called *valve regulated lead*
cells are operating effectively in ma
batteries. For a detailed account of lea
(1992), Hirai (1990), and Moore (19
introduced special versions of sealed
energy density; for example, the Po
series and the Bolder Technologies Cc
with comparatively higher energy den
Nelson, 1997).

9.4.2.1 Discharge Perform

The general shape of the dischar
(if the current is uniform) is shown in
starved-electrolyte sealed-lead acid ba
until most of its capacity is discharge
and the length of the voltage plateau
major features of sealed-lead cells and
leaves the plateau and begins to declin
the curve. Starved-electrolyte sealed-l
a wide range of temperatures. They m
ronments and may produce actual cap
when used in hot environments. Figur
capacity and cell temperature. Actual
rated capacity as measured at 23°C.

nd extensively damaged by less than
at fail-safe circuits to disconnect the
ertemperature conditions usually are

the form and replace the function of
ally more expensive, they cost less
sposable batteries. They are the least
or low current applications and have
y have the shortest cycle life in deep

in automobiles because they are the
rge currents. Lead-acid batteries also
/e well for classic "floating" appli-
logy is popular for automobile and
ies serve the electronic engineering
as the least capacity by volume and

d disadvantages of the five chemis-
driven by the technical requirements

ies

asically uses the design developed by
multiple plates immersed in a pool of
al, so water is consumed throughout
corrosive and explosive gases when
ance-free forms of flooded batteries
water loss throughout a normal life
oded batteries are found in motive
wer backup. Today, other forms of
eries in small- and medium-capacity
-acid batteries continue to dominate.
tteries is starting, lighting, and igni-
rge flooded lead-acid batteries also
g from forklifts to submarines and
electrical applications, most notably

s

ed in commercial use in the early
the sealed cell are the same as other

forms of lead-acid batteries, the key difference is the recombination process that occurs in the sealed cell as it reaches full charge. In conventional flooded lead-acid systems, the excess energy from overcharging goes into the electrolysis of water in the electrolyte with the resulting gases being vented. This occurs because the excess electrolyte prevents the gases from diffusing to the opposite plate and possibly recombining. Thus, electrolyte is lost on the overcharge and must be replenished. The sealed-lead cell, like the sealed nickel-cadmium cell, uses recombination to reduce or eliminate this electrolyte loss.

Sealed lead-acid batteries for electronics applications are somewhat different from the type commonly found in the automobile. There are two types of sealed lead-acid batteries: the original gelled electrolyte and retained (or absorbed) system. The gelled electrolyte system is obtained by blending silica gel with an electrolyte, causing it to set up in gelatin form. The retained system employs a fine glass fiber separator to absorb and retain liquid electrolyte. Sometimes the retained system is called an absorbed glass mat (AGM). The AGM also is known as a *starved design*. *Starved* means the absorption limits of the glass separator create a limitation to the AGM design relating to diffusion properties of the separator. In certain cases, the AGM battery must be racked and trayed in a specific position for optimum performance. Both types, gelled and AGM, are called *valve regulated lead acid* (VRLA) systems. Today, sealed-lead cells are operating effectively in many markets previously closed to lead-acid batteries. For a detailed account of lead-acid cells, see Gates Energy Products Inc. (1992), Hirai (1990), and Moore (1993). Meanwhile, some manufacturers have introduced special versions of sealed lead-acid batteries with higher volumetric energy density; for example, the Portable Energy Products, Inc., Thinline™ series and the Bolder Technologies Corporation Thin Metal Film (TMF™), both with comparatively higher energy densities (Moneypenny and Wehmeyer, 1994; Nelson, 1997).

9.4.2.1 Discharge Performance of Sealed-Lead Acid Cells

The general shape of the discharge curve, voltage as a function of capacity (if the current is uniform) is shown in Figure 9-2. The discharge voltage of the starved-electrolyte sealed-lead acid battery typically remains relatively constant until most of its capacity is discharged. It then drops off sharply. The flatness and the length of the voltage plateau relative to the length of the discharge are major features of sealed-lead cells and batteries. The point at which the voltage leaves the plateau and begins to decline rapidly often is identified as the knee of the curve. Starved-electrolyte sealed-lead acid batteries may be discharged over a wide range of temperatures. They maintain adequate performance in cold environments and may produce actual capacities higher than their standard capacity when used in hot environments. Figure 9-3 illustrates the relationships between capacity and cell temperature. Actual capacity is expressed as a percentage of rated capacity as measured at 23°C.

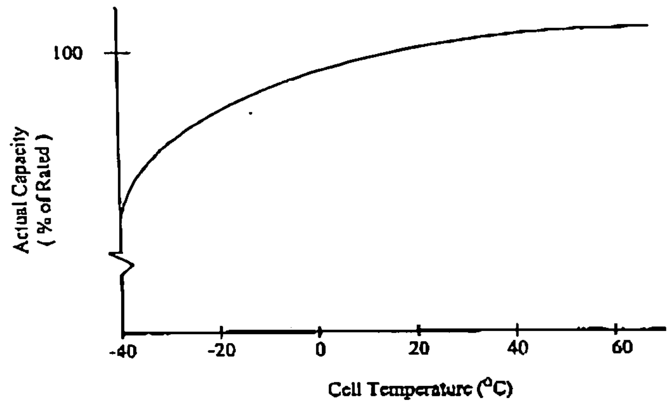


FIGURE 9-3 Typical discharge capacity as a function of cell temperature

9.4.2.2 Capacity During Battery Life

The initial actual capacity of sealed-lead acid batteries is almost always lower than the battery's rated or standard capacity. However, during the battery's early life, the actual capacity increases until it reaches a stabilized value, which usually is above the rated capacity. The number of charge/discharge cycles or length of time on float charge required to develop a battery's capacity depends on the specific regime employed. Alternatively, a battery that is on charge at 0.1 C usually is stabilized after receiving a 300% (of rated capacity) overcharge. The process may be accelerated by charging and discharging at low rates.

Under normal operating conditions, the battery's capacity will remain at or near its stabilized value for most of its useful life. Batteries then will begin to suffer some capacity degradation due to their age and the duty to which they have been subjected. This permanent loss usually increases slowly with age until the capacity drops below 80% of its rated capacity, which often is defined as the end of useful battery life. Figure 9-4 shows the capacity variation with cycle life that can be expected from sealed-lead acid batteries.

9.4.2.3 Effect of Pulse Discharge on Capacity

In some applications, the battery is not called on to deliver a current continuously. Rather, energy is drawn from the battery in pulses. By allowing the battery to "rest" between these pulses, the total capacity available from the battery is increased. Figure 9-5 shows typical curves representing the voltage delivered as a function of discharged capacity for pulsed and constant discharge at the same rate.

For the pulsed curve, the upper line represents the open-circuit voltage and the lower line represents the voltages during the periods when the load

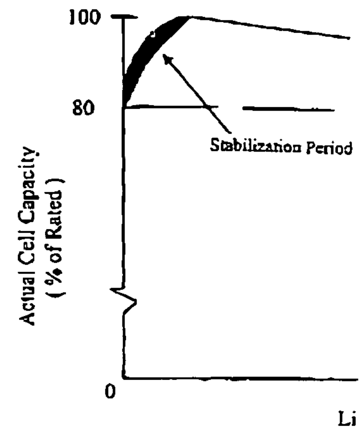


FIGURE 9-4 Typical cell's capacity c

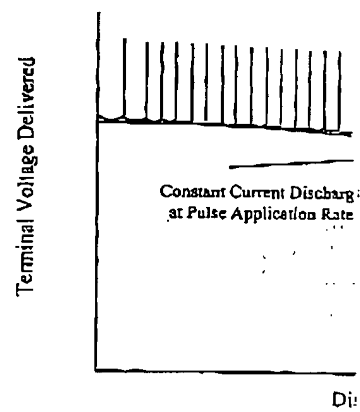
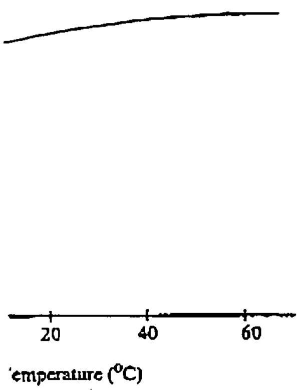


FIGURE 9-5 Typical pulsed and const

is connected. The use of discharged ca
periods and shows only the periods of

9.4.3 Charging

In general, experience with seale
that application problems are more lik
overcharging. Since the starved-electro
from overcharging, designers may wa
charged, even at the expense of some de
overcharging, either in magnitude or du



a function of cell temperature

y Life

.ead acid batteries is almost always
pacity. However, during the battery's
l it reaches a stabilized value, which
umber of charge/discharge cycles or
velop a battery's capacity depends on
, a battery that is on charge at 0.1 C
(of rated capacity) overcharge. The
d discharging at low rates.
: battery's capacity will remain at or
:ful life. Batteries then will begin to
ıeir age and the duty to which they
ıually increases slowly with age until
apacity, which often is defined as the
the capacity variation with cycle life
batteries.

ge on Capacity

called on to deliver a current continu-
ery in pulses. By allowing the battery
ıpacity available from the battery is
representing the voltage delivered as
d and constant discharge at the same

represents the open-circuit voltage
; during the periods when the load

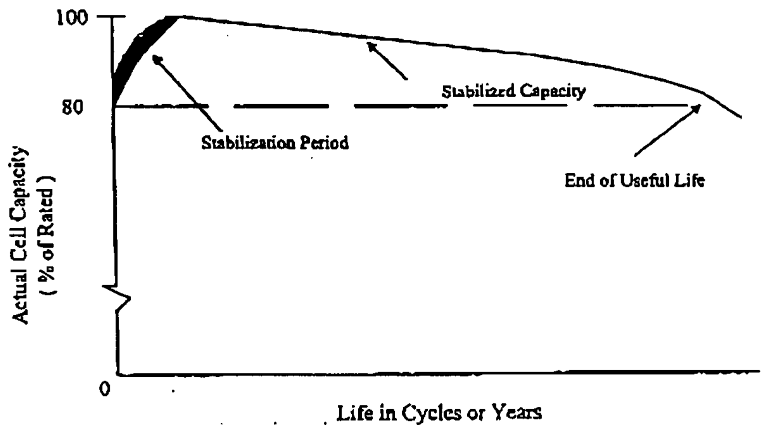


FIGURE 9-4 Typical cell's capacity during its life

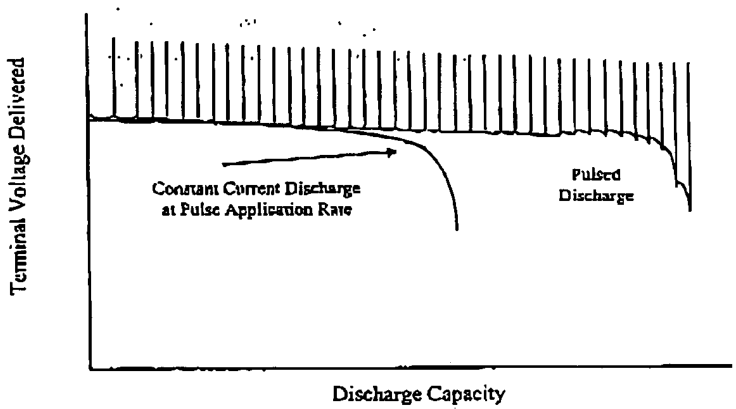


FIGURE 9-5 Typical pulsed and constant discharge curves

is connected. The use of discharged capacity as the abscissa eliminates the rest periods and shows only the periods of useful discharge.

9.4.3 Charging

In general, experience with sealed-lead acid cells and batteries indicates that application problems are more likely to be caused by undercharging than overcharging. Since the starved-electrolyte cell is relatively resistant to damage from overcharging, designers may want to ensure that the batteries are fully charged, even at the expense of some degree of overcharge. Obviously, excessive overcharging, either in magnitude or duration, still should be avoided.

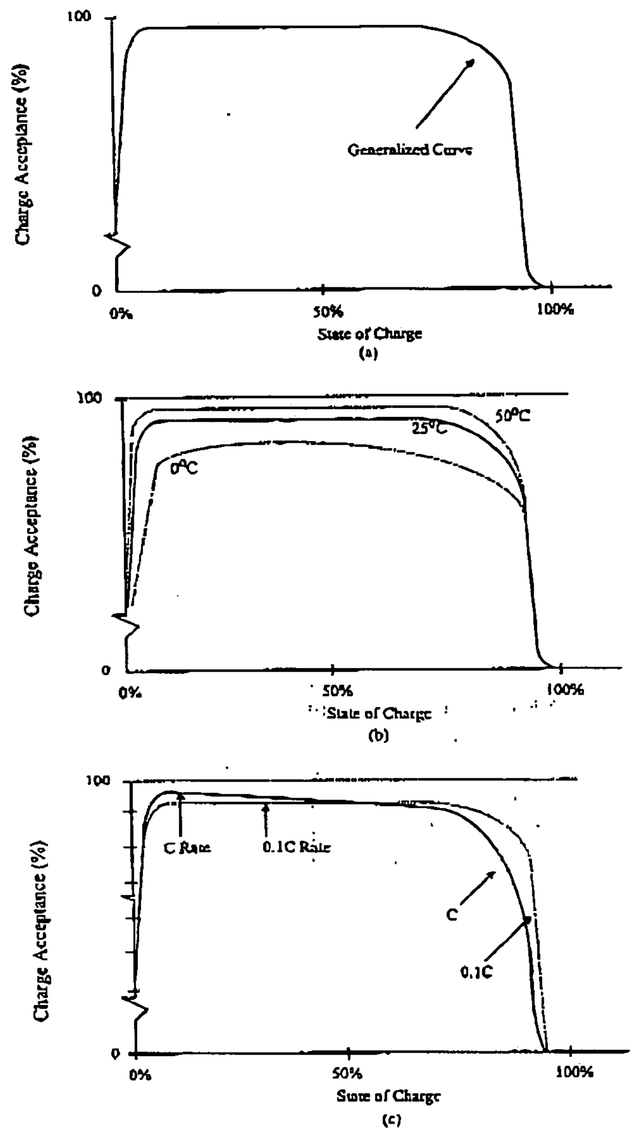


FIGURE 9-6 Charge acceptance: (a) effect of state of charge on charge acceptance, (b) charge acceptance at various temperatures, (c) charge acceptance at various charge rates

The charge acceptance of seal quite high, typically greater than 90 every ampere-hour of charge introd deliver 0.9 Ah to a load. Charge acc including cell temperature, charge ra charging (Figure 9-6).

The state of charge of the cell, with which the cell will accept a c the charge acceptance initially is qu charged, it accepts current more readi approaching 98% in some situations. until the cell approaches full charge.

As mentioned earlier, as the cel trical energy begins generating gas, w When the cell is fully charged, essent except for the very small current that would be manifested as self-discharg phenomena is shown in Figure 9-6(a)

As with most chemical reaction charging reactions in the sealed-lea higher temperatures than at lower tem as shown in Figure 9-6(b).

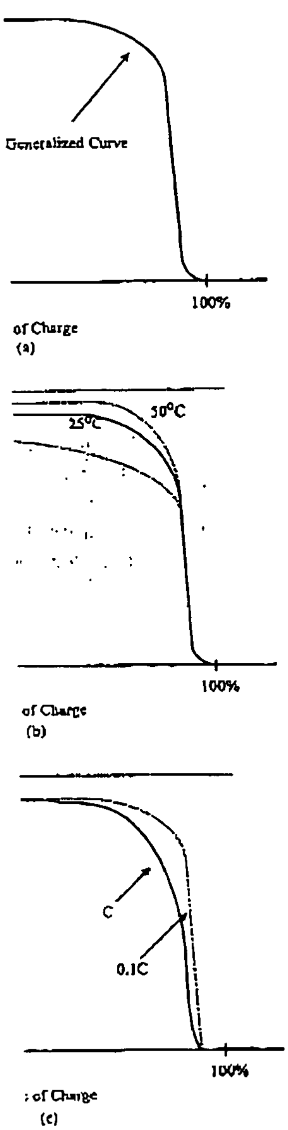
The starved-electrolyte sealed-l charging rates. The cell can accept a c as long as the state of charge is not s the cell can be charged at low rates w

Figure 9-6(c) shows the generaliz defined by charging rates. When exam of charge, low charge rates provide b

In the starved-electrolyte sealed-l bulk of the gases is recombined and t the cell if it is overcharged.

9.5 Nickel-Cadmium Batte

Sealed NiCd batteries are especi self-contained power source increases Among the significant advantages of N discharge rates, fast recharge capability places NiCd families at the top of us the NiCd batteries are capable of ope in any orientation with reasonable con



of state of charge on charge acceptance, (c) charge acceptance at various charge

The charge acceptance of sealed-lead acid batteries in most situations is quite high, typically greater than 90%. A 90% charge acceptance means that for every ampere-hour of charge introduced into the cell, the cell will be able to deliver 0.9 Ah to a load. Charge acceptance is affected by a number of factors including cell temperature, charge rate, state of charge, age, and the method of charging (Figure 9-6).

The state of charge of the cell, to some extent, will dictate the efficiency with which the cell will accept a charge. When the cell is fully discharged, the charge acceptance initially is quite low. As the cell becomes only slightly charged, it accepts current more readily and the charge acceptance jumps quickly, approaching 98% in some situations. The charge acceptance stays at a high level until the cell approaches full charge.

As mentioned earlier, as the cell becomes fully charged, some of the electrical energy begins generating gas, which represents a loss in charge acceptance. When the cell is fully charged, essentially, all the charging energy generates gas, except for the very small current that makes up for internal losses that otherwise would be manifested as self-discharge. A generalized curve representing these phenomena is shown in Figure 9-6(a).

As with most chemical reactions, temperature has a positive effect on the charging reactions in the sealed-lead acid cell. Charging is more efficient at higher temperatures than at lower temperatures, all other parameters being equal, as shown in Figure 9-6(b).

The starved-electrolyte sealed-lead cell charges very efficiently at most charging rates. The cell can accept a charge at accelerated rates (up to the C rate) as long as the state of charge is not so high that excessive gas is generated. And the cell can be charged at low rates with excellent charge acceptance.

Figure 9-6(c) shows the generalized curve of charge acceptance now further defined by charging rates. When examining these curves, note that, at high states of charge, low charge rates provide better charge acceptance.

In the starved-electrolyte sealed-lead acid cell at typical charging rates, the bulk of the gases is recombined and there is virtually no venting of gases from the cell if it is overcharged.

9.5 Nickel-Cadmium Batteries

Sealed NiCd batteries are especially well suited to applications where a self-contained power source increases the versatility or reliability of the product. Among the significant advantages of NiCd families are higher energy density and discharge rates, fast recharge capability, and long operating and storage life. This places NiCd families at the top of usage in the portable products. In addition, the NiCd batteries are capable of operating over a wide temperature range and in any orientation with reasonable continuous overcharge capability.

9.5.1 Construction

NiCd secondary batteries operate at 1.2 V, using nickel oxyhydroxide for the active material in the positive electrode. The active material of the negative electrode consists of cadmium, and an alkali solution acts as the electrolyte. In NiCd batteries, a reaction at the negative electrode consumes the oxygen gas that generates at the positive electrode during overcharging. The design prevents the negative electrode from generating hydrogen gas, permitting a sealed structure. NiCd batteries mainly adopt cylindrical or prismatic configurations.

9.5.2 Discharge Characteristics

The discharge voltage of a sealed NiCd cell typically remains relatively constant until most of its capacity is discharged. It then drops off rather sharply. The flatness and length of the voltage plateau relative to the length of discharge are major features of sealed NiCd cells and batteries. The discharge curve, when scaled by considering the effects of all the application variables, provides a complete description of the output of a battery. Differences in design, internal construction, and conditions of actual use of cell affect the performance characteristics. As an example, Figure 9-7 illustrates the typical effect of discharge rate.

9.5.3 Charge Characteristics

Nickel-cadmium batteries are charged by applying a current of proper polarity to the terminals of the battery. The charging current can be pure direct current (DC) or it may contain a significant ripple component such as half-wave or full-wave rectified current.

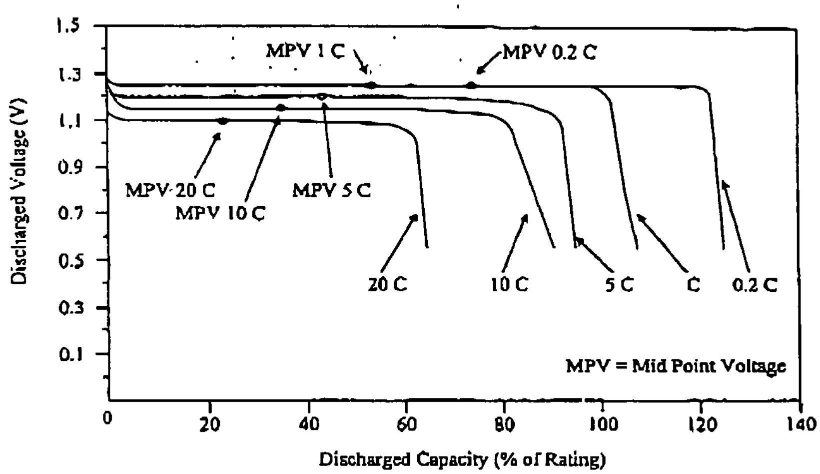


FIGURE 9-7 Discharge curves for NiCd cells: (a) typical curves at 23°C, (b) voltage depression effect

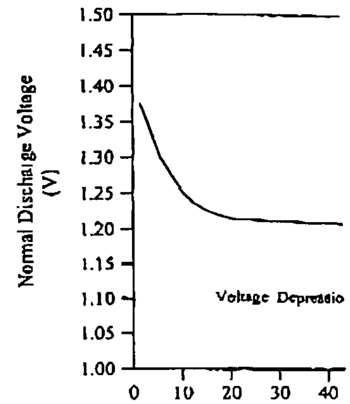


FIGURE 9-7 Continued

This section on charging sealed r
rates as multiples (or fractions) of the
be categorized into descriptive terms,
charge, or trickle charge as shown in

When a nickel-cadmium battery i
to converting the active material to a
also goes to converting active materia
is lost in parasitic side reactions.

Figure 9-8 shows the charge acce
no charge acceptance loss, would be
to the cell could be retrieved on disc
accept charge at different levels of eff
of the cell, as shown by the bottom c

Figure 9-8 describes this perfor
behavior (zones 1, 2, 3, and 4). Each
mechanisms responsible for loss of ch

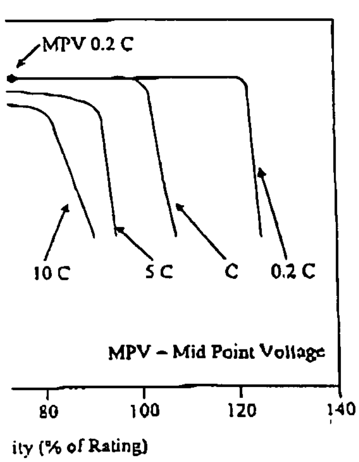
TABLE 9-2 Categories of rates for cha

Method of Charging	*Charge rate (multiples of C rate)*
Standard	0.05
	0.1
Quick	0.2
	0.25
	0.33
Fast	1
	2
	4
Trickle	0.02–0.1

V, using nickel oxyhydroxide for
The active material of the negative
solution acts as the electrolyte. In
rode consumes the oxygen gas that
rcharging. The design prevents the
gas, permitting a sealed structure.
ismatic configurations.

d cell typically remains relatively
ed. It then drops off rather sharply.
relative to the length of discharge
atteries. The discharge curve, when
application variables, provides a
ery. Differences in design, internal
cell affect the performance charac-
the typical effect of discharge rate.

y applying a current of proper po-
harging current can be pure direct
ipple component such as half-wave



: (a) typical curves at 23°C, (b) voltage

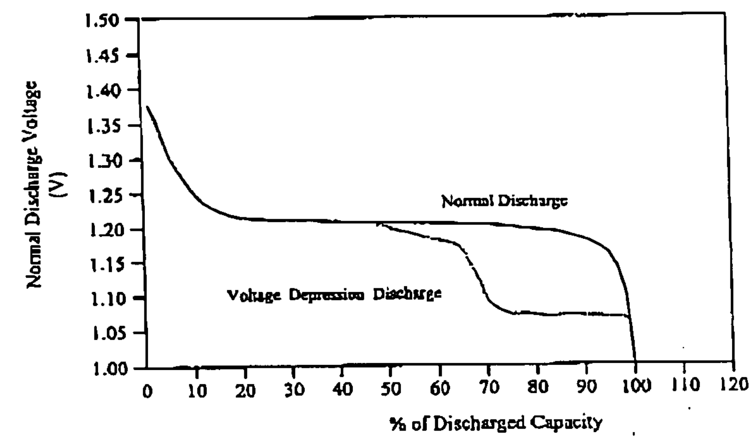


FIGURE 9-7 Continued

This section on charging sealed nickel-cadmium batteries refers to charging rates as multiples (or fractions) of the C rate. These C rate charging currents can be categorized into descriptive terms, such as standard charge, quick charge, fast charge, or trickle charge as shown in Table 9-2.

When a nickel-cadmium battery is charged, not all of the energy input goes to converting the active material to a usable (chargeable) form. Charge energy also goes to converting active material into an unusable form, generates gas, or is lost in parasitic side reactions.

Figure 9-8 shows the charge acceptance of NiCd cells. The ideal cell, with no charge acceptance loss, would be 100% efficient. All the charge delivered to the cell could be retrieved on discharge. But nickel-cadmium cells typically accept charge at different levels of efficiency, depending on the state of charge of the cell, as shown by the bottom curve of Figure 9-8.

Figure 9-8 describes this performance for successive types of charging behavior (zones 1, 2, 3, and 4). Each zone reflects a distinct set of chemical mechanisms responsible for loss of charge input energy.

TABLE 9-2 Categories of rates for charging NiCd cell

Method of Charging	*Charge rate (multiples of C rate)*	*Recharge Time (hours)*	*Charge Control*
Standard	0.05	36–48	Not required
	0.1	16–20	
Quick	0.2	7–9	Not required
	0.25	5–7	
	0.33	4–5	
Fast	1	1.2	
	2	0.6	
	4	0.3	Required
Trickle	0.02–0.1	Used for maintaining a fully charged battery	

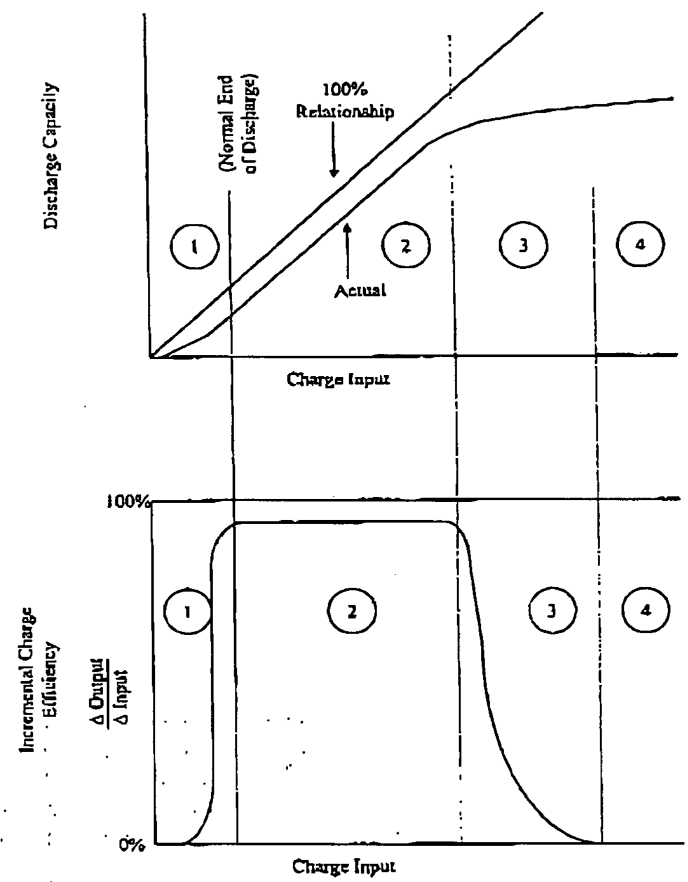


FIGURE 9-8 Charge acceptance of a sealed NiCd cell at 0.1 C and 23°C

In zone 1, a significant portion of the charge input converts some of the active material mass to an unusable form; that is, charged material not readily accessible during medium- or high-rate discharges, particularly in the first few cycles. In zone 2, the charging efficiency is only slightly less than 100%; small amounts of internal gas and parasitic side reactions are all that prevent the charge from being totally efficient. Zone 3 is transition region.

As the cell approaches a full charge, the current input shifts from charging positive active material to generating oxygen gas. In the overcharge region, zone 4, all the current coming into the cell generates gas. In this zone, the charging efficiency is practically none.

The boundaries between zones 1, 2, 3, and 4 are indistinct and vary depending on cell temperature, construction, and charge rate. The level of charge

acceptance in zones 1, 2, and 3 also i: rate. For details, see Gates Energy Pr

9.5.4 Voltage Depression

When some NiCd batteries are cycles and overcharging, cell voltage of the capacity is consumed. This is the resulting lower voltage may be proper system operation, giving the in Figure 9-7(b)). If cells are exposed to atures, and this is quite common, the the normal cell voltage. Voltage depı tion that disappears when the cell is voltage depression effect sometimes and clearing the same by charging an

9.6 Nickel-Metal Hydride I

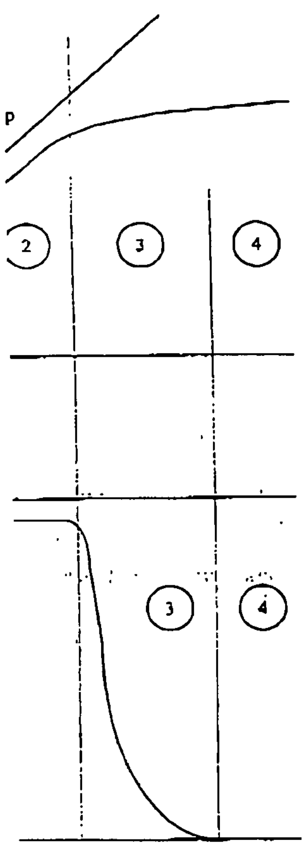
For those battery users who nec willing to pay a higher price, an opı which offer a significant increase in NiCd cell technology to a new chen applications such as notebook comput NiMH batteries entered the market in

In many ways, nickel-metal hydr They use nickel for the positive elect hydrogen-absorbing alloy, for the neg of 1.2 V, they provide high capacity, ı

The NiCd cell is more tolerant NiMH cells. NiCd cells hold their ch will withstand 500–2000 charge/disch for NiMH cells. Further, NiCd cells v NiMH cells.

On the other hand, NiMH cells sel that NiCd cells sometimes do. As with applications are higher than those of Ni 1993; Briggs, 1994).

The voltage profile of NiMH cell of the NiCd cells. NiMH cells' open- discharge rates, NiMH cells' output vol have relatively constant output voltage typical graph from a battery company. NiCd and 1100 mAh NiMH AA cell greater capacity results in approximate



NiCd cell at 0.1 C and 23°C

charge input converts some of the
hat is, charged material not readily
:harges, particularly in the first few
only slightly less than 100%; small
.ctions are all that prevent the charge
tion region.
e current input shifts from charging
gen gas. In the overcharge region,
ll generates gas. In this zone, the

, and 4 are indistinct and vary de-
nd charge rate. The level of charge

acceptance in zones 1, 2, and 3 also is influenced by cell temperature and charge rate. For details, see Gates Energy Products (1992).

9.5.4 Voltage Depression Effect

When some NiCd batteries are subjected to numerous partial discharge cycles and overcharging, cell voltage decreases below, 1.05 V/cell before 80% of the capacity is consumed. This is called the **voltage depression effect**; and the resulting lower voltage may be below the minimum voltage required for proper system operation, giving the impression that the battery has worn out (see Figure 9-7(b)). If cells are exposed to overcharging, particularly at higher temperatures, and this is quite common, the voltage may be about 150 mV lower than the normal cell voltage. Voltage depression is an electrically reversible condition that disappears when the cell is completely discharged and recharged. The voltage depression effect sometimes is called erroneously the **memory effect**, and clearing the same by charging and discharging is called conditioning.

9.6 Nickel-Metal Hydride Batteries

For those battery users who need high power in a small package and are willing to pay a higher price, an option is the nickel-metal hydride families, which offer a significant increase in cell power density. These extensions of NiCd cell technology to a new chemistry have become popular with product applications such as notebook computers and cellular phones. The first practical NiMH batteries entered the market in 1990.

In many ways, nickel-metal hydride batteries are the same as NiCd types: They use nickel for the positive electrode but a recently developed material, a hydrogen-absorbing alloy, for the negative electrode. With an operating voltage of 1.2 V, they provide high capacity, more energy density than NiCd models.

The NiCd cell is more tolerant of fast recharging and overcharging than NiMH cells. NiCd cells hold their charge longer than NiMH cells. NiCd cells will withstand 500–2000 charge/discharge cycles, compared to about 500 cycles for NiMH cells. Further, NiCd cells withstand a wider temperature range than NiMH cells.

On the other hand, NiMH cells seldom exhibit the notorious "memory effect" that NiCd cells sometimes do. As with any new technology, the prices for NiMH applications are higher than those of NiCds (Small, 1992; Eager, 1991; Furukawa, 1993; Briggs, 1994).

The voltage profile of NiMH cells during discharge is very similar to that of the NiCd cells. NiMH cells' open-circuit voltage is 1.3–1.4 V. At moderate discharge rates, NiMH cells' output voltage is 1.2 V. Both NiCd and NiMH cells have relatively constant output voltage during their useful service. Figure 9-9 is a typical graph from a battery company, comparing the output voltage of 700 mAh NiCd and 1100 mAh NiMH AA cells under load. Note that the NiMH cell's greater capacity results in approximately 50% longer service life.

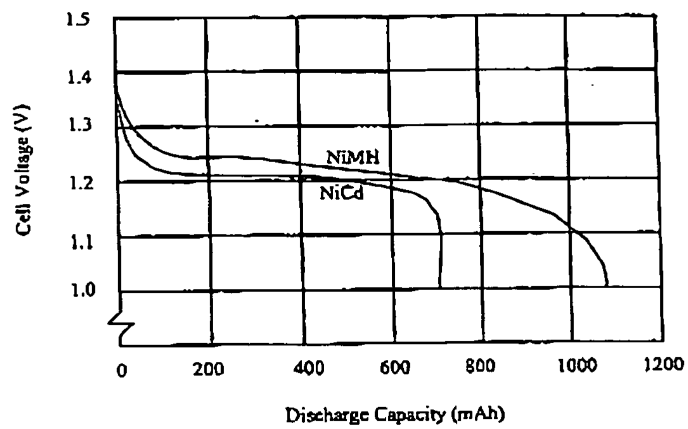


FIGURE 9-9 Discharge characteristics of NiCd and NiMH batteries

Figure 9-10 is another typical battery company graph showing that NiCd and NiMH batteries and cells charge in a similar fashion as well. However, the little bumps at the end of the two cell's charge curves bare closer examination. You always will see these negative excursions. even though absolute cell voltages vary significantly with temperature.

The negative excursions signal a fully charged cell more or less independent of temperature, a useful quirk that sophisticated battery chargers exploit. Note that the NiCd cell's negative-going voltage excursion after reaching a full charge is more pronounced than that of the NiMH cell.

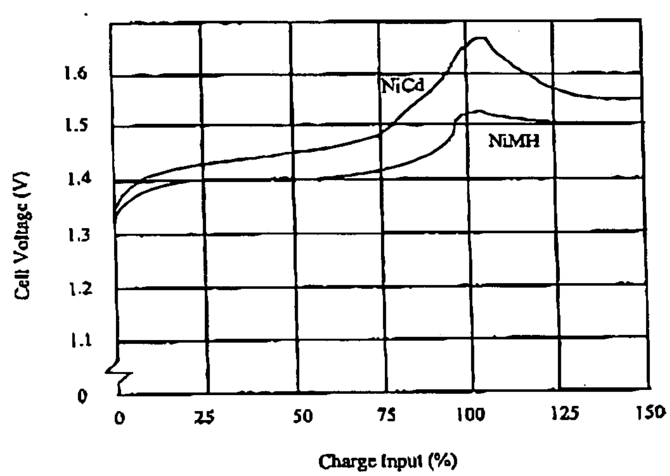


FIGURE 9-10 Battery voltage at the achievement of 100% charge

There are several reasons for re

- NiCd batteries contain cadmium, v
- NiMH has nearly the same opera changeable.
- NiMH batteries have 30–40% hig NiCd batteries.
- NiMH batteries have a 90-minute c

9.7 Lithium-Ion Batteries

The demand for portable systems competitive, companies are offering li Meeting these goals requires improve tional NiCd and NiMH systems.

Li-ion is a promising technolog size and weight of a battery pack. ' twice that of nickel-based chemistry (: lighter weight packs of acceptable cap. cell voltage of NiCd and NiMH batter required voltage. The Li-ion batteries a and many other portable systems beca costs, and readily available manageme

The first noticeable difference b is the higher internal impedance of

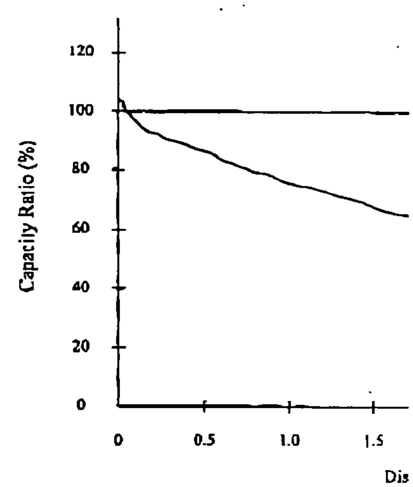


FIGURE 9-11 Li-ion and NiCd capac